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CONCEPTION DE LA CHAÎNE LOGISTIQUE DES BIORAFFINERIES FORESTIÈRES INTÉGRÉES ET VERTES

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DÉDICACE

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RÉSUMÉ

L’industrie forestière canadienne est un puissant moteur qui contribue au développement économique et social du pays. Cependant, depuis quelques années, cette industrie et principalement celle des pâtes et papiers (P&P) opère dans un contexte économique difficile qui est dû entre autres à la faible demande pour les produits papetiers de base, à la concurrence étrangère et la diminution du dollar canadien par rapport au dollar américain. Identifier de nouvelles gammes de produits pour enrichir celle existante semble être une solution intéressante pour l'industrie canadienne de P&P afin de surmonter cette crise et de demeurer compétitive.

D'autre part, plusieurs milliards de tonnes de combustibles fossiles sont consommées annuellement dans le monde. L'utilisation de ces sources d'énergie est la cause principale de plusieurs problèmes environnementaux notamment les pluies acides et l'augmentation de la concentration du dioxyde de carbone dans l'atmosphère [1, 2]. D'autres facteurs tels que la hausse des prix de ces réserves d'énergies et l'incertitude quant à leur disponibilité à long terme ont encouragé le développement des produits renouvelables.

La conversion de la biomasse en bioproduits à valeur ajoutée et à faible empreinte de carbone dans un contexte de bioraffinerie forestière intégrée et verte (BRFIV) semble être une solution prometteuse pour remédier à l'ensemble des problèmes cités.

Le concept de la BRFIV peut être défini comme un complexe industriel intégré, composé d'une usine de P&P et d'une unité de bioraffinage. Cette dernière est capable de transformer la biomasse lignocellulosique en une grande variété de produits, générant ainsi des profits pour l'ensemble de la BRFIV et éliminant l’utilisation de l’énergie fossile.

Plusieurs procédés de conversion biochimiques et thermochimiques peuvent être implantés dans l'unité de bioraffinage forestier à savoir la fermentation, la pyrolyse ou la gazéification. Bien que les bioraffineries biochimiques de première génération prennent de plus en plus d'ampleur, les bioraffineries de deuxième génération, notamment les bioraffineries de gazéification n'ont pas encore vu le jour. Ceci est dû principalement au coût élevé du procédé de gazéification, sa complexité et son degré de maturité. Toutefois, cette technologie est capable d'annuler la dépendance des industries papetières aux énergies fossiles, de proposer une panoplie de

bioproduits et reste flexible par rapport à la matière première utilisée. L'intégration des bioraffineries de gazéification dans des usines de pâtes et papiers canadiennes pourrait alors assurer la compétitivité de ces dernières et en même temps diminuer les impacts environnementaux associés à l'implémentation de ce complexe.

Toutefois, la configuration de la chaîne logistique des bioraffineries de gazéification intégrées n'est pas encore établie au Canada. En effet, étant donné qu'il est possible d'utiliser diverses matières premières, de générer une variété de bioproduits et d'alimenter plusieurs industries pétrochimiques, chaque maillon de la chaîne de valeur doit être défini et optimisé ainsi que la chaîne entière afin de garantir la viabilité économique et environnementale du complexe. De plus, le choix des usines de P&P canadiennes favorables pour une transformation en BRFIV doit être déterminé en tenant compte de la disponibilité de la matière première ainsi que de leurs emplacements par rapport aux industries chimiques.

L’objectif de cette thèse s'insère dans ce contexte. Il s'agit de contribuer au développement des bioraffineries forestières intégrées et vertes à travers la conception optimale de la chaîne logistique de la bioraffinerie de gazéification intégrée aux usines de P&P. En d'autres termes, il s'agit de conduire au développement d'outils d'aide à la décision intégrant des indicateurs économiques et environnementaux pour déterminer les emplacements optimaux des bioraffineries intégrées aux usines papetières, le choix de la source de biomasse et de la méthode de récupération correspondante, le choix du bioproduit à générer, les capacités optimales des unités de bioraffinage, le réseau de distribution optimal ainsi que les flux de matières échangés entre les unités de la BRFIV. Le but est de maximiser la rentabilité économique ainsi que la viabilité environnementale des BRFIV. Les critères de décision considérés sont les coûts totaux de production, les émissions de gaz à effet de serre ainsi que la consommation évitée des ressources fossiles.

L'outil d'aide à la décision est basé sur des modèles mathématiques de planification stratégique et tactique et intègre des indicateurs environnementaux calculés à partir d'analyse de cycle de vie de scenarios de chaîne logistique. Il a été appliqué à deux études de cas comparant les provinces de l'est et de l'ouest du Canada et deux types de bioraffineries de gazéification à savoir les bioraffineries de production du méthanol et du diesel Fischer-Tropsch.

Les résultats ont permis de mettre en avant les alternatives et les scenarios de chaîne logistique les plus intéressants et ceux à écarter aussi bien au niveau économique qu'au niveau environnemental. Ils ont démontrés également que le Canada a le potentiel de générer de la gazoline contenant jusqu'à 10 % en volume de méthanol produit à partir de biomasse forestière. Une teneur en carburant renouvelable de 4 %, basée sur le volume de carburant diesel pourrait être entièrement satisfaite dans l'ouest du Canada en exploitant la biomasse accessible dans un rayon de 150 km des usines de pâtes existantes.

ABSTRACT

The Canadian forest industry has been for a long time a significant contributor to the economic and social development of the country. However, during the last two decades, the forest sector, and mainly the Pulp and Paper (P&P) industry, has been operating in a challenging economic environment, due in part to the declining market demand for traditional paper products, the price competition and the Canadian dollar weakness against its American counterpart. Identifying new products to enlarge the existing platform has appeared to be a promising opportunity for the Canadian P&P industry to overcome this crisis and remain competitive.

On the other hand, several billion tons of fossil fuels are consumed annually in the world. The use of these resources is the main cause of several environmental problems, namely the acid rain and the increase of the carbon dioxide concentration in the atmosphere [1, 2]. Other factors such as the uncertainties concerning fossil fuels availability and prices have encouraged the development of bioproducts.

Biomass conversion into bioproducts with low carbon footprint in the context of the Green Integrated Forest Biorefinery (GIFBR) could be a promising contribution to climate change, dependence on fossil resources, and P&P mills profit grow.

The GIFBR concept can be defined as an integrated industrial complex, composed of a P&P receptor mill and a biorefinery unit for the production of wide range of bioproducts. The transition of the P&P mill to a GIFBR generates new profit streams and eliminates the use of fossil fuels resources.

A range of biochemical and thermochemical conversion processes can be deployed in the biorefinery unit, including fermentation, pyrolysis or gasification. First generation biorefineries that are built around biochemical conversion technologies are extensively explored. However, second generation biorefineries based on thermochemical processes, such as gasification based-biorefineries, are under development due to the high cost and complexity of the process in addition to its low level of maturity. Nonetheless, gasification is a flexible technology regarding feedstock type and provides a wide range of bioproducts alternatives combined with the subsequent syngas conversion pathways. The integration of gasification based-biorefineries in the

P&P mills could ensure nil fossil fuels consumption and an economic viability of the GIFBR complex.

However, the optimal configuration of the GIFBR supply chain is not yet established in Canada. Since it is possible to use various raw materials, to generate a variety of bioproducts and to feed several petrochemical industries, each link of the value chain must be defined and optimized as well as the entire chain in order to ensure the economic and environmental viability of the GIFBR complex. In addition, the potential sites for biorefining activities must be identified taking into account the location of the P&P mills and the availability of biomass feedstocks.

The purpose of this thesis is to contribute to the development of the GIFBR concept through the design of the optimal supply chain related to the gasification-based GIFBR. The ultimate goal is to develop decision-making tools, based on strategic and tactical models, that integrate economic and environmental indicators to determine the optimal biomass feedstock type and the corresponding biomass treatment methods, the location and capacity of the GIFBR, the choice of the bioproduct to be generated and the flows of feedstocks and biofuels between biomass procurement sites, GIFBR and demand industries (petroleum refineries). The production cost is selected to be the quantitative measure of the economic objective while the environmental performance of the GIFBR supply chain is evaluated with respect to greenhouse gases emissions and fossil fuel consumption based on the life cycle analysis.

The applicability of the proposed model is illustrated through two case studies representing the Eastern and Western Canada and involving two biofuels alternatives, namely methanol and F-T diesel. The results allow to select the most interesting alternatives and supply chain scenarios from economical and environmental perspectives. They show that, by valorizing forest biomass within a radius of 150 km from the GIFBR, Canada has the potential to synthesis gasoline containing up to 10 % biomethanol. However, only Western Canada could produce diesel with 4% renewable content which exceed the blend mandate fixed by the federal government (2% renewable content).

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ACV	Analyse du Cycle de Vie
BRFIV	Bioraffinerie Forestière Intégrée et Verte
CTL	Cut To Length
F-T	Fischer-Tropsch
FT	Full Tree
GAMS	Generalized Algebraic Modeling System
GES	Gaz à Effet de Serre
GHG	Greenhouse Gas
GIFBR	Green Integrated Forest Biorefinery
GIS	Geographic Information System
IRR	Internal Rate of Return
KgCO2eq	Kilogramme d'équivalents en dioxyde de carbone
LCA	Life Cycle Analysis
MILP	Mixed Integer Linear Programming
MSP	Minimum Selling Price
P&P	Pâtes et Papiers
PC	Pouvoir Calorifique
PLNE	Programme Linéaire en Nombre Entier
PMH	Productive Machine Hour
TRR	Target Rate of Return

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CHAPITRE 1 INTRODUCTION

1.1 Contexte

L'industrie forestière canadienne est un puissant moteur qui contribue au développement économique et social du pays. Cependant, depuis quelques années, cette industrie et principalement celle des pâtes et papiers (P&P) opère dans un contexte économique difficile qui est dû entre autres à la faible demande pour les produits papetiers de base et à l'augmentation des coûts de l'énergie et des produits chimiques. Plusieurs autres facteurs contribuent également à renforcer la crise financière que connait cette industrie, à savoir la concurrence étrangère et la diminution de la valeur du dollar canadien par rapport au dollar américain. Identifier de nouvelles gammes de produits pour enrichir celle existante semble être une solution intéressante pour l'industrie canadienne de P&P afin de surmonter cette crise et de demeurer compétitive.

D'autre part, plusieurs milliards de tonnes de combustibles fossiles sont consommées annuellement dans le monde. L'utilisation de ces sources d'énergie est la cause principale de plusieurs problèmes environnementaux notamment les pluies acides, le smog photochimique et l'augmentation de la concentration du dioxyde de carbone dans l'atmosphère [1, 2]. D'autres facteurs tels que la hausse des prix de ces réserves d'énergies et l'incertitude quant à leur disponibilité à long terme ont encouragé le développement des produits renouvelables (ou bioproduits).

La conversion de la biomasse en bioproduits à valeur ajoutée et à faible empreinte de carbone dans un contexte de bioraffinerie forestière intégrée et verte (BRFIV) semble être une solution prometteuse pour remédier à l'ensemble des problèmes cités. Le concept de la BRFIV peut être défini comme un complexe industriel intégré composé d'une usine de P&P et d'une unité de bioraffinage. Cette dernière est capable de transformer la biomasse lignocellulosique en une grande variété de produits, générant ainsi des profits pour l'ensemble de la BRFIV et éliminant l'utilisation de l'énergie fossile.

Plusieurs procédés de conversion biochimiques et thermochimiques peuvent être implantés dans l'unité de bioraffinage forestier à savoir la fermentation, la pyrolyse, la combustion ou la gazéification.

La gazéification est une voie de transformation thermochimique qui permet, en présence d'un oxydant, la conversion des matières carbonées, à savoir, la biomasse lignocellulosique en un gaz de synthèse (ou syngaz) riche en monoxyde de carbone et en dihydrogène [3].

L'intérêt s'est orienté dans ce projet vers la bioraffinerie de gazéification pour l'intégrer aux usines papetières. En effet, il s'agit de l'unique procédé capable d'annuler la dépendance de ces industries aux énergies fossiles, garantir l'aspect vert de la BRFIV et élargir, en même temps, la gamme de produits générés.

Ce projet de doctorat se penche sur l'implémentation de la BRFIV et plus précisément sur la conception de la chaîne de valeur de la bioraffinerie de gazéification intégrée aux usines de P&P.

1.2 **Problématique**

Bien que le concept de bioraffinage prenne de plus en plus d'ampleur et suscite davantage l'intérêt des chercheurs et des industriels grâce aux différents avantages qu'il offre, les bioraffineries de deuxième génération notamment les bioraffineries de gazéification ne sont pas nombreuses (seulement deux unités à New Westminster et à Kamloops en Colombie Britannique) Ceci est dû principalement au coût élevé du procédé de gazéification, sa complexité et son degré de maturité. Toutefois, seule cette technologie est capable de garantir la réduction de la consommation des ressources fossiles, de proposer une panoplie de bioproduits et est flexible par rapport à la matière première utilisée. L'intégration des bioraffineries de gazéification dans des usines de P&P canadiennes pourrait alors assurer la compétitivité de ces dernières et diminuer le risque financier associé à l'implémentation de ce complexe en partageant l'infrastructure mise en place et les ressources disponibles.

Toutefois, la problématique réside dans la conception de la chaîne de valeur des bioraffineries de gazéification intégrées, qui n'est pas encore établie. En effet, étant donné qu'il est possible d'utiliser une panoplie de matières premières, de générer une variété de bioproduits et d'alimenter plusieurs industries pétrochimiques, chaque maillon de la chaîne de valeur doit être défini et optimisé afin de garantir la viabilité économique et environnementale du complexe. De plus, le choix des usines de P&P canadiennes favorables pour une transformation en BRFIV doit être

déterminé en tenant en compte de la disponibilité de la matière première ainsi que de leurs emplacements par rapport aux industries chimiques.

1.3 Objectif

L'objectif de cette thèse est de contribuer au développement des bioraffineries forestières intégrées et vertes à travers la conception optimale de la chaîne logistique de la bioraffinerie de gazéification intégrée, depuis l'étape d'approvisionnement en biomasse lignocellulosique, jusqu'à la livraison des bioproduits finaux. Ceci a pour but de minimiser les impacts environnementaux de la BRFIV tout en maximisant ses profits. En d'autres termes, il s'agit de conduire au développement d'un modèle mathématique intégrant des indicateurs économiques et environnementaux pour l'optimisation de la chaîne de valeur de la BRFIV.

1.4 Organisation de la thèse

Ce mémoire de thèse comprend neuf chapitres et est appuyé par 4 articles soumis. Le contexte du projet, la problématique ainsi que l'objectif sont décrits dans ce chapitre 1. La revue de la littérature est résumée dans le chapitre 2, suivie par l'approche méthodologique dans le chapitre 3. Les quatre articles sont exposés dans les chapitres 4, 5, 6 et 7. Enfin, la discussion générale et la conclusion détaillant les contributions scientifiques ainsi que les recommandations pour les travaux futurs sont présentées respectivement dans les chapitres 8 et 9.

Le premier article présente les résultats de l'évaluation économique des différentes alternatives de valorisation du gaz de synthèse dans une bioraffinerie de gazéification intégrée. Le deuxième article s'intéresse au calcul des impacts environnementaux liés aux différents scénarios de chaîne logistique de la bioraffinerie de gazéification. Les articles 3 et 4 portent sur l'optimisation économique et environnementale de la chaîne de valeur des bioraffineries de gazéification intégrées.

CHAPITRE 2 REVUE DE LA LITTÉRATURE

2.1 Le concept du bioraffinage

Le bioraffinage est un concept analogue au raffinage pétrolier, toutefois, il a l'avantage d'utiliser la biomasse, une matière première renouvelable et abondante. Il représente donc une voie prometteuse au niveau environnemental et économique. Le bioraffinage permet de générer une vaste gamme de produits tels que la bioénergie (chaleur, électricité), les bioproduits chimiques (méthanol, ammoniac, hydrogène, etc.) ou les biocarburants (biodiesel, bio-gazoline, bioéthanol, etc.) au moyen de divers procédés biochimiques et thermochimiques [4, 5] (Figure 2-1).

Les procédés biochimiques convertissent les sucres contenus dans la biomasse en biocarburants liquides (éthanol, butanol, etc.) et gazeux (méthane, etc.), respectivement, par fermentation et par digestion anaérobie.

Les procédés thermochimiques, la combustion, la gazéification et la pyrolyse, permettent de transformer, sous l'action de la chaleur et selon le taux d'oxygène introduit, tous les composants de la biomasse en un combustible solide (charbon), liquide (huile pyrolytique) ou gazeux (vapeur d'eau, gaz de synthèse).

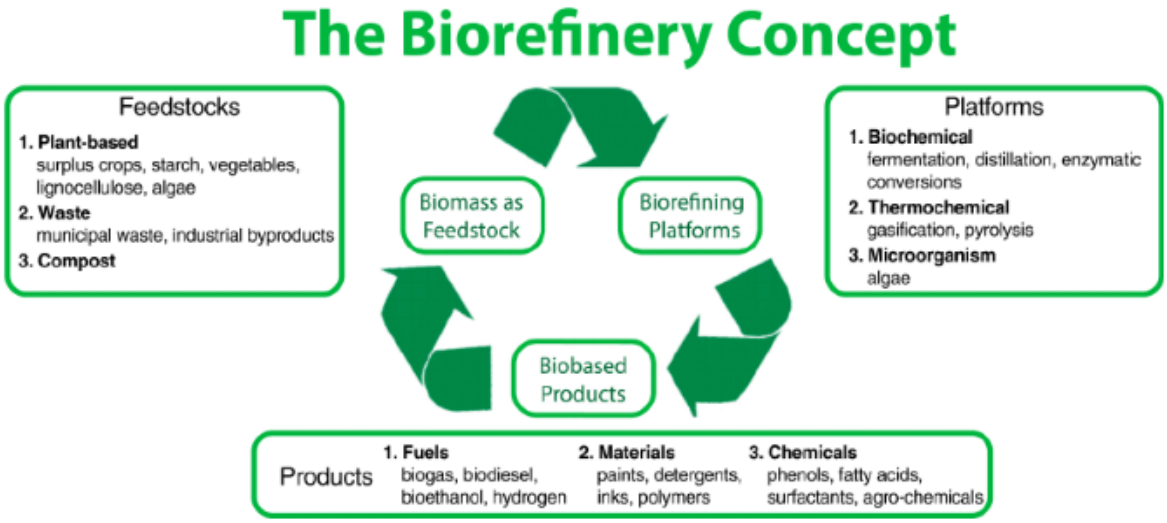

Figure 2-1: Concept global du bioraffinage

2.2 La bioraffinerie intégrée basée sur la de gazéification

Le procédé de gazéification présente plusieurs avantages comparativement aux autres procédés de conversion thermochimique, notamment la combustion. La gazéification est capable d'éliminer la dépendance aux ressources fossiles à travers la production du gaz de synthèse, de biocarburants ou de bioproduits chimiques. De plus, le rendement de conversion de l'ensemble gazéification/système de cogénération est bien meilleur que celui de l'ensemble chaudière/système de cogénération (étant donné que les moteurs et les turbines à gaz peuvent atteindre des rendements plus élevés que les turbines à vapeur et que les combustibles gazeux, ayant des caractéristiques de combustion améliorées, brûlent plus efficacement que les combustibles solides. Enfin, sur le plan environnemental, comme la température de combustion est plus élevée, les émissions générées sont plus importantes. Par ailleurs, les contaminants contenus dans le gaz de synthèse tels que les gaz acides ou l'ammoniac sont éliminés d'une manière efficace entrainant des émissions beaucoup plus faibles [6].

Le bioraffinage forestier intégré, moyennant un procédé de gazéification, permet de générer de nombreux produits énergétiques et chimiques à partir de ressources forestières. L'intégration de ce procédé aux usines papetières permet de tirer profit des avantages de chacun. En effet, les bioraffineries bénéficient ainsi des infrastructures mises en place (vapeur, électricité, eau, produits chimiques, entrepôts, etc.), de l'expertise en matière de chimie de bois, des importantes chaînes d'approvisionnement de la matière première à faible distance et des réseaux de distribution déjà en place. Les usines de P&P bénéficient également de cette collaboration puisque l'unité de gazéification permet d'annuler leur dépendance aux énergies fossiles (utiliser le gaz de synthèse pour remplacer le gaz naturel dans les fours à chaux et initier les chaudières à biomasse), d'élargir les sources de biomasse à leur disposition, d'acquérir de nouveaux marchés et ainsi générer de nouveaux profits. Enfin, la bioraffinerie de gazéification représente une alternative attrayante aux industries pétrochimiques vu l'abondance des ressources forestières canadiennes disponibles.

2.3 Procédé de gazéification de la biomasse

La gazéification est la conversion thermochimique de la biomasse en présence d'une quantité réduite d'agent oxydant (oxygène, air, vapeur d'eau) et à très haute température. Elle conduit à la formation d'un gaz de synthèse riche en vapeur d'eau, en dihydrogène (H_2), en monoxyde de carbone (CO), en dioxyde de carbone (CO_2) et en méthane (CH_4)[7].

La proportion de chaque espèce dépend du type de biomasse choisi (contenu énergétique, composition, humidité), de la technologie de gazéification mise en jeu et des paramètres de contrôle du procédé de gazéification (nature et quantité d'oxydant, qualité de traitement du gaz de synthèse, etc.) [8].

Le gaz de synthèse peut être utilisé comme [9]:

- source de production de chaleur par combustion,
- source de production d'électricité et de chaleur par cogénération, ou
- source de production de carburants et de produits chimiques par traitements catalytiques.

2.3.1 Les réactions chimiques mises en jeu

Le processus de gazéification se déroule en quatre étapes successives :

2.3.1.1 Étape de pyrolyse

La réaction de pyrolyse se déroule en absence d'oxygène et à des températures situées entre 120°C et 600°C. Elle libère des composants volatiles et un combustible solide (coke) très riche en carbone et contenant des matières minérales (cendres). La matière volatile est constituée de gaz incondensables (hydrogène, monoxyde carbone, dioxyde de carbone, hydrocarbures gazeux) et de gaz condensables (vapeur d'eau, goudrons, etc.). La proportion en matières volatiles et en combustible solide varie selon les paramètres réactionnels et la composition de la biomasse [10].

2.3.1.2 Étape d'oxydation homogène

Les matières volatiles réagissent avec l'oxygène à des températures comprises entre 1200°C et 1500°C pour former, d'une part, l'énergie nécessaire aux autres phases et, d'autres part, de la

vapeur d'eau et du dioxyde de carbone qui vont réagir avec le carbone lors de la phase de réduction [10].

2.3.1.3 Étape d'oxydation hétérogène

Une partie du combustible solide riche en carbone formé lors de l'étape de pyrolyse réagit avec l'oxygène afin de fournir la chaleur nécessaire pour alimenter les réactions de pyrolyse et de gazéification. La consommation en coke doit être limitée car le carbone doit être disponible pour la réaction de gazéification [10].

2.3.1.4 Étape de gazéification (réduction)

Elle correspond à l'étape de conversion du carbone résiduel. Les atomes de carbone réagissent avec la vapeur d'eau et le dioxyde de carbone formés lors des réactions d'oxydation pour former un gaz combustible [10].

Les réactions mises en jeu lors des 4 étapes sont présentées dans le Table 2-1.

Tableau 2-1: Réactions mises en jeu lors de la gazéification

Étape d'oxydation homogène	$CO + \frac{1}{2} O_2 \leftrightarrow CO_2$	$\Delta H = -283\ KJ/mol$
	$CO + H_2O \leftrightarrow CO_2 + H_2$	$\Delta H = -41\ KJ/mol$
	$H_2 + \frac{1}{2} O_2 \leftrightarrow H_2O$	$\Delta H = -242\ KJ/mol$
	$CH_4 + 2\ O_2 \leftrightarrow CO_2 + 2\ H_2O$	$\Delta H = -800\ KJ/mol$
	$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$	$\Delta H = +206\ KJ/mol$
Étape d'oxydation hétérogène	$C + O_2 \leftrightarrow CO_2$	$\Delta H = -394\ KJ/mol$
	$C + \frac{1}{2} O_2 \leftrightarrow CO$	$\Delta H = -111\ KJ/mol$
Étape de gazéification	$C + H_2O \leftrightarrow CO + H_2$	$\Delta H = +131\ KJ/mol$
	$C + CO_2 \leftrightarrow 2CO$	$\Delta H = +172\ KJ/mol$
	$C + 2H_2 \leftrightarrow CH_4$	$\Delta H = -75\ KJ/mol$

2.3.2 Les réacteurs de gazéification

Il existe trois principaux types de réacteurs de gazéification : les lits fixes, les lits fluidisés et les lits entrainés. Le principe de fonctionnement de ces réacteurs reste identique puisque toutes les réactions thermochimiques sont présentes. Cependant, la différence réside dans le mode

d'introduction de la biomasse, l'agent oxydant mis en jeu, la nature du réacteur ou encore le mode d'évacuation des cendres. Le choix d'un type de procédé est guidé par différents paramètres tels que la taille de l'installation, le combustible utilisé, l'usage du syngaz produit etc. [7, 11, 12].

Les gazéificateurs à lit fixe sont de construction simple, permettent un contrôle des températures et des vitesses de réactions et assurent un bon contact entre la phase gazeuse et la phase solide. Les gazéificateurs à lit fixe peuvent fonctionner soit à contre-courant soit à co-courant [9, 13].

Dans les réacteurs à lit fixe fonctionnant à contre-courant, le combustible est alimenté par le haut du réacteur alors que l'agent oxydant est introduit par le bas. Les matières volatiles pyrolysées en partie haute du gazéificateur sont entraînées directement vers la sortie du gazéificateur par le gaz de synthèse. Ce dernier renferme donc des composés hydrocarbonés tels que le méthane ainsi que des composés aromatiques condensables à savoir le goudron [9]. Les gazéificateurs à lit fixe sont souvent utilisés pour des installations à usage thermique.

Dans les procédés fixes à co-courant, la biomasse et l'agent oxydant se déplacent dans le même sens. Le gaz de synthèse produit est donc évacué de la partie la plus chaude, soit le bas du réacteur. La concentration en goudron est par conséquence beaucoup plus faible et l'efficacité du procédé est plus élevée par rapport au procédé à contre-courant [9]. Les lits fixes à co-courant sont utilisés dans des installations de petites et moyennes puissances, inférieures à 500 kWe.

Pour les gazéificateurs à lit fluidisé, le combustible est mélangé dans un lit de matériau inerte, tel que le sable ou la silice [13]. Les cendres et le carbone non réagis sont dirigés vers la partie supérieure du réacteur et séparés du gaz de synthèse produit par un cyclone. Les lits fluidisés sont adaptés aux grandes puissances (entre 1 et 1000 MWe) et couvrent une large gamme de produits [14]. Il existe deux types de réacteurs à lit fluidisé : dense (bouillonnant) et circulant. Bien que leur principe de fonctionnement soit similaire, certaines caractéristiques les distinguent comme : la vitesse de fluidisation, la température de fonctionnement et la granulométrie de la matière constituant le lit et celle du combustible. Dans les deux conceptions, le gaz produit sort à la même température que dans tout le lit (900-1000°C) [15].

Dans les gazéificateurs à lit entraîné, la conversion de la source de carbone est plus complète avec un rendement supérieur à 99 %. Le gaz de synthèse ne comprend pas de composés

condensables ou de goudrons. Le seul hydrocarbure présent dans le gaz est donc le méthane, en faible proportion [9]. Toutefois, le combustible solide doit être broyé avant d'être injecté dans le gazéificateur sous forme pulvérulente ou bien sous forme de boue.

2.3.3 Prétraitement de la biomasse

La réaction de gazéification ne représente qu'une étape du procédé complet de gazéification. Le gazéificateur se trouve en effet associé en amont à une unité de prétraitement de la matière première et en aval à des unités de nettoyage et de conditionnement du gaz de synthèse [3].

Lors de l'étape de prétraitement, la matière première humide est broyée puis stockée dans un réservoir [3]. Elle est ensuite introduite dans une unité de séchage où le taux d'humidité est réduit à une valeur comprise entre 10 et 20 %. Le principal avantage du séchage de la biomasse est d'éviter d'utiliser l'énergie dans le gazéificateur pour chauffer et sécher la biomasse [3]. Les systèmes de séchage utilisent de l'air, des gaz de combustion chauds (provenant d'un procédé en aval) ou de la vapeur surchauffée (lorsque des systèmes de cogénération sont utilisés) [3]. L'utilisation de la vapeur assure un meilleur transfert de la chaleur et donc un temps de séjour plus court. Par contre le principal inconvénient des systèmes de séchage utilisant les gaz de combustion est le risque élevé d'incendie.

La biomasse séchée atteint ensuite le système d'alimentation [8]. Il faut noter que la biomasse lignocellulosique utilisée dans les installations de gazéification peut provenir de diverses sources. Les opérations de prétraitement de cette matière première sont similaires dans leur principe, quelle que soit l'origine de la biomasse utilisée et quelle que soit la technologie de gazéification envisagée [8].

2.3.4 Traitement et conditionnement du gaz de synthèse

Le gaz de synthèse issu de la gazéification de la biomasse contient des contaminants dont il faut réduire ou éliminer totalement selon le niveau de tolérance aux impuretés (polluants) de l'application envisagée. Le syngaz doit ensuite être conditionné afin d'optimiser les paramètres des procédés de conversion en aval.

2.3.4.1 **Impuretés présentes dans le gaz de synthèse**

- Les particules solides. C'est l'ensemble de la matière inorganique minérale à savoir les cendres, le carbone résiduel qui n'a pas réagi dans le gazéificateur et les matériaux utilisés pour maintenir les particules du lit en suspension [3].

- Les goudrons. Ce sont des hydrocarbures aromatiques polycycliques condensables plus lourds que le benzène. Ils sont produits à partir de matières volatilisées après polymérisation. La teneur en goudrons dépend de la matière première utilisée et du procédé de gazéification mis en jeu [3].

- Les gaz acides. Ce sont principalement le dioxyde de carbone (CO_2) et le sulfure d'hydrogène (H_2S). Le sulfure présent dans la biomasse se transforme principalement en H_2S lors de la gazéification. Une faible quantité de sulfure de carbonyle (COS) pourrait également être présente dans la composition du gaz de synthèse formé.

- Les composants alcalins. Les composants alcalins tels que l'oxyde de calcium (CaO) ou l'oxyde de potassium (K_2O) sont présents dans certains types de biomasse. Une fois la biomasse gazéifiée, ces composants se vaporisent. La condensation de ces derniers à partir d'une température de 650°C entraine la désactivation des catalyseurs ainsi que la corrosion des équipements [3].

- Ammoniac. L'azote contenu dans la biomasse ou l'air se transforme en ammoniac (NH_3). Ce polluant entraine la corrosion du cuivre, du zinc et de nombreux alliages. Il peut conduire à la désactivation des catalyseurs utilisés lors de la conversion du syngaz.

2.3.4.2 **Technologies de traitement des impuretés**

Afin d'éliminer ou de réduire la quantité d'impuretés présente dans le gaz de synthèse, des procédés propres à chaque contaminant sont déjà disponibles et d'autres sont au niveau expérimental ou de recherche.

- Refroidissement du gaz de synthèse: Le gaz de synthèse doit être refroidi avant son traitement. Ceci peut être accompli de deux manières différentes, soit par injection directe d'eau, soit par l'intermédiaire d'un échangeur de chaleur. L'injection directe d'eau permet, en plus, d'éliminer les goudrons, les espèces alcalins et les particules solides résiduelles [3].

- Élimination des particules solides: Afin d'éliminer les particules solides contenues dans le syngaz, il faut utiliser, à la sortie du réacteur, un dispositif de séparation physique ou réaliser une filtration à chaud. Dans les systèmes de séparation physique tels que les cyclones, les particules doivent être éliminées avant le refroidissent du gaz de synthèse afin d'éviter la condensation des goudrons sur les particules entrainant le colmatage des équipements. Les filtres métalliques ou céramiques opèrent au-dessus des températures de condensation des goudrons.

- Élimination des goudrons: Plusieurs méthodes de traitement des goudrons existent ou sont en voie de développement. On cite le traitement physique (lavage humide), le traitement thermique et le craquage catalytique. Le traitement physique par injection d'eau permet de réduire le volume des goudrons jusqu'à moins de 10 ppm [3]. Le lavage humide élimine par la même occasion une grande partie de l'ammoniac, les hydrocarbures de longues chaînes et presque la totalité de la vapeur d'eau contenue dans le gaz [8]. Le craquage catalytique se produit à des températures d'environ 800°C dans un lit fluidisé circulant en présence de dolomite comme catalyseur. Ce dernier améliore le reformage des hydrocarbures en composés gazeux plus légers [8]. Le craquage thermique élimine les goudrons à des températures allant jusqu'à 1200°C. L'importante énergie requise peut rendre ce procédé peu concurrentiel [3].

- Élimination des gaz acides: Les gaz acides peuvent être éliminés par trois procédés différents utilisant des solvants chimiques, solvants physiques ou absorbants catalytiques. Des solvants à base d'amine sont généralement utilisés pour l'élimination des gaz acides par voie chimique. L'élimination physique tire profit de la grande solubilité du H_2S en utilisant un solvant organique. Le niveau de tolérance aux gaz acides est bas surtout pour la synthèse des carburants et des produits chimiques. Dans ce cas, un catalyseur à base d'oxyde de zinc est utilisé dans un réacteur à lit fixe additionnel afin d'éliminer les quantités résiduelles de contaminants [3].

- Élimination des composés alcalins: L'élimination des métaux alcalins peut s'effectuer pendant le lavage à l'eau du gaz de synthèse ou à l'aide de filtres et de dépoussiéreurs électrostatiques [8].

- Élimination de l'ammoniac: Le nettoyage par voie humide permet d'éliminer l'ammoniac formé. Lorsque un craquage catalytique ou thermique est employé, l'ammoniac est transformé en hydrogène et en azote [3].

2.3.4.3 **Conditionnement du gaz de synthèse**

Le conditionnement du gaz de synthèse comprend l'étape de reformage des hydrocarbures légers et la réaction de conversion du gaz à l'eau.

- Reformage du gaz de synthèse: Le gaz de synthèse peut contenir des hydrocarbures légers indésirables pour la synthèse de certains produits chimiques et carburants. La conversion de ces hydrocarbures peut se faire soit par reformage à la vapeur (*'Steam Reforming'*) ou par reformage auto-thermique (*'Autothermal reforming'*). Le reformage à la vapeur transforme les hydrocarbures légers en CO et en H_2 par ajout de la vapeur d'eau en présence d'un catalyseur à base de nickel, par contre, le reformage autothermique combine l'oxydation partielle des hydrocarbures dans la première partie du réacteur avec l'action de la vapeur dans sa seconde partie [16].

- Conversion du gaz à l'eau *'Water Gas Shift'*: La conversion du gaz à l'eau est utilisée pour convertir une fraction du CO en H_2 en présence de l'eau afin d'ajuster le rapport stœchiométrique H_2/CO [16] exigé pour la synthèse des différents bioproduits et biocarburants.

2.4 **Voies de valorisation du gaz de synthèse**

Il existe trois principales voies de valorisation du gaz de synthèse issu de la gazéification de la biomasse à savoir :

- La production d'énergie: le gaz de synthèse peut soit être directement brulé dans une chaudière, soit utilisé pour alimenter un moteur à combustion interne ou des turbines à gaz. La combustion du gaz de synthèse dans une chaudière est l'application la plus simple, car le syngaz n'a pas à être refroidi, ni débarrassé des goudrons et des poussières. L'utilisation d'un moteur à combustion interne ou d'une turbine à gaz requiert cependant que les contaminants soient éliminés afin d'éviter la corrosion des composants de la turbine [14].

- La synthèse des carburants liquides et des produits chimiques: le gaz de synthèse peut également être valorisé en nombreux produits chimiques et en biocarburants par des procédés de transformation thermocatalytique [14].

La Figure 2-2 illustre les différentes voies de valorisation du gaz de synthèse [14].

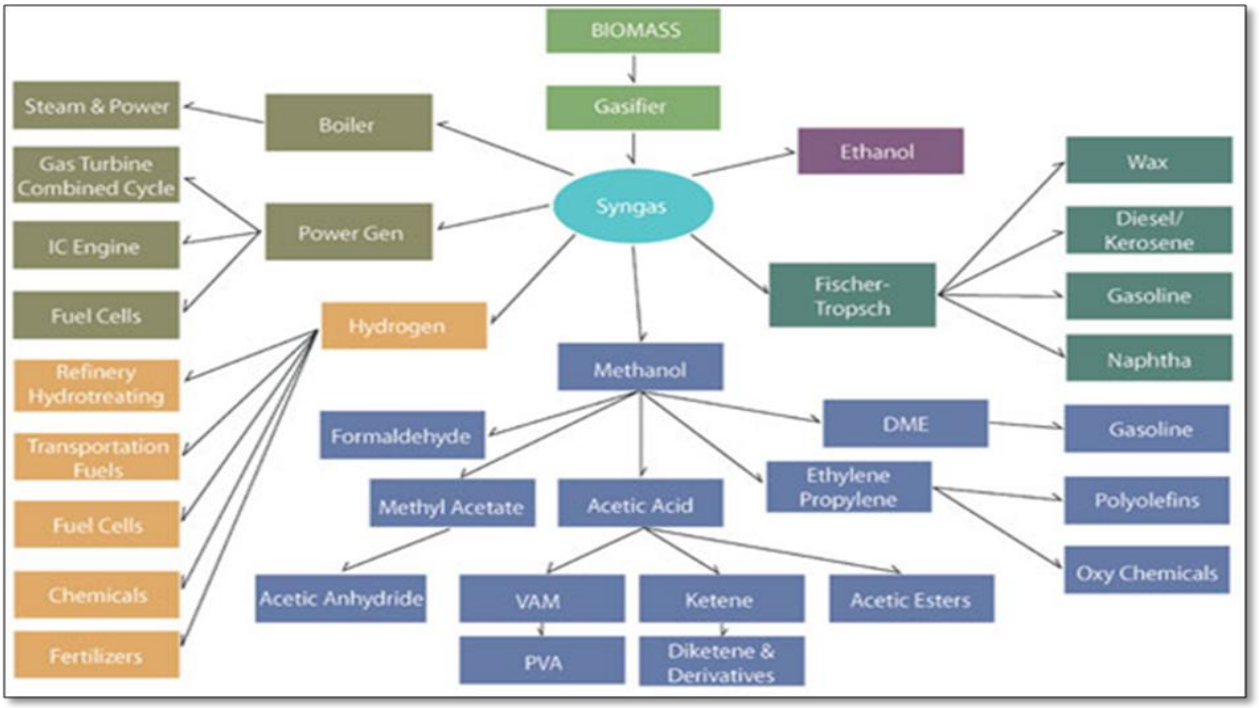

Figure 2-2: Voies de valorisation du gaz de synthèse

2.4.1 La cogénération

Dans les systèmes de cogénération, l'électricité est générée par combustion du gaz de synthèse dans une turbine à gaz fournissant un travail mécanique au générateur. La vapeur récupérée est à son tour utilisée pour produire de l'électricité moyennant une turbine à vapeur. Le rendement des systèmes de cogénération de la biomasse à grande échelle (supérieure à 100 MW) est de l'ordre de 35% à 40% [3].

2.4.2 Synthèse du diésel Fischer-Tropsch

Le procédé Fischer-Tropsch (F-T) permet la production d'un mélange d'hydrocarbures, de différentes longueurs, constitué de diésel, de gazoline et de cire. Le diésel F-T a été produit à partir du charbon par la société Sasol en Afrique du sud [3] . La société Shell a relancé l'intérêt pour cette filière en construisant une unité utilisant le gaz naturel comme matière première en Malaisie [7]. La réaction de conversion catalytique FT est fortement exothermique et produit une grande variété d'alcanes (Équation 1). Pour la production de gazoline, des températures élevées

allant de 300°C à 350°C et des catalyseurs à base de fer sont généralement employés. Par contre, pour la production du diésel, des températures plus basses (entre 200°C et 240°C) et des catalyseurs à base de cobalt sont utilisés [3].

$$CO + 2.1\,H_2 \rightarrow -(CH_2)- + H_2O \qquad (1)$$

2.4.3 Synthèse du méthanol

Le méthanol est produit commercialement par reformage auto thermique ou à la vapeur du méthane [3]. La réaction de synthèse du méthanol à partir de gaz de synthèse purifié est exothermique (équation 2) et se produit en présence d'un catalyseur ($Cu/ZnO/Al_2O_3$) à des températures allant de 220°C à 275°C et des pressions de 50 à 100 bar. Le taux de conversion total du CO en CH_3OH est typiquement de 99%, cependant le taux de conversion par passage direct est seulement de 25% [3]. Une étape de distillation est nécessaire pour éliminer l'eau du méthanol [15].

$$CO + 2\,H_2 \leftrightarrow CH_3OH \qquad (2)$$

2.4.4 Synthèse de l'ammoniac

La production de l'ammoniac, à partir de gaz de synthèse propre, se fait principalement en trois étapes [17]. Le gaz de synthèse réagit en premier lieu avec la vapeur d'eau à une température d'environ 900°C pour former du dihydrogène et du dioxyde de carbone. Le produit pénètre ensuite dans un adsorbeur à modulation de pression ('*Pressure Swing Adsorption*') [15] pour produire du dihydrogène pur. Ce dernier réagit avec l'azote de l'air à haute pression (80- 200 bar) et à haute température (350-480 °C) en présence d'un catalyseur à base de fer. La réaction de synthèse de l'ammoniac se fait selon le procédé '*Haber-Bosch*' (Équation 3). Le taux de conversion de N_2 et de H_2 par passage direct dans le réacteur de synthèse de l'ammoniac est d'environ 25 à 35% [18]. Par conséquent, un système de recyclage est employé pour améliorer l'efficacité du procédé.

$$N_2 + 3\,H_2 \leftrightarrow 2\,NH_3 \qquad (3)$$

2.4.5 Synthèse de l'éthanol

Dans le cas de l'éthanol, le gaz de synthèse réagit à environ 70 bar et 300 °C en présence d'un catalyseur (Molybdenum disulfide) pour former un mélange d'alcool composé de méthanol, d'éthanol, de propanol, de butanol et de pentanol. Une première colonne à distillation est utilisée pour récupérer le méthanol et l'éthanol. L'éthanol et ensuite séparé du méthanol dans une seconde colonne de distillation [19].

2.5 La biomasse lignocellulosique

2.5.1 Composition de la biomasse lignocellulosique

La matière lignocellulosique représente la source de carbone renouvelable la plus abondante de la planète avec une production annuelle mondiale de 10^{10} MT [20]. Elle est composée principalement de cellulose, d'hémicelluloses et de lignine. Ces trois macromolécules sont à l'origine de la structure complexe et très résistante de la biomasse lignocellulosique [21].

La cellulose est un polysaccharide constitué d'une longue chaîne de molécules de glucose. Le degré de polymérisation de ce polymère est variable et dépend de la nature de la biomasse. Il se situe entre 800 et 10000 unités [21]. La formation de liaisons hydrogène entre les molécules de cellulose confère la structure fibreuse à la cellulose.

Les hémicelluloses sont des polymères de sucres à 6 carbones tels que le glucose, le mannose et le galactose et de sucres à 5 carbones à savoir le xylose et l'arabinose [21]. Contrairement à la cellulose, les chaînes d'hémicelluloses sont plus courtes avec un degré de polymérisation ne dépassant pas les 200 unités [20], de plus, ces polysaccharides sont facilement dégradables vu leurs structure amorphe [21].

La lignine est un polymère aromatique amorphe tridimensionnel très complexe. Les unités structurales de la lignine (monolignols) sont l'alcool 4-coumarylique, l'alcool conifférylique et l'alcool sinapylique [21]. La combinaison de ces trois mono-lignols par des liaisons chimiques diverses et sans caractère ordonné confère la structure amorphe de la lignine et la rend très résistante aux attaques chimiques et à la dégradation microbienne [20].

2.5.2 Sources de la biomasse lignocellulosique

La biomasse lignocellulosique provient de divers types de ressources. Les résidus, à savoir les déchets de récolte (agricoles et forestiers) et les déchets des industries de bois, constituent une première source. Les matières ligneuses non marchandes, forment un deuxième gisement [7]. La Figure 2-3 illustre les sources de la biomasse lignocellulosique.

2.5.2.1 Les résidus (agricoles et forestiers) et les déchets de transformation de bois

Les résidus agricoles et forestiers: les résidus agricoles sont définis comme étant les parties des plantes non utilisées. Il peut s'agir aussi bien de pailles de céréales ou de colza, de tiges de maïs, etc. Ce type de déchets est en concurrence avec l'alimentation des bétails. La quantité de ces résidus est très variable en fonction des cultures [7]. Les déchets d'exploitation forestière sont constitués de branches et rameaux provenant du façonnage des arbres abattus, des feuilles, etc.

Les déchets des industries de transformation de bois: ils sont constitués de résidus secondaires et tertiaires. Les résidus secondaires regroupent les résidus industriels provenant des scieries et des industries des pâtes et papiers à savoir les écorces, les sciures, les copeaux et la liqueur noire. Les résidus tertiaires comprennent le bois de récupération provenant de la construction et de la démolition [7].

2.5.2.2 La matière lignocellulosique non marchande (les cultures dédiées, le bois mort)

Les cultures énergétiques dédiées: les cultures énergétiques dédiées sont réalisées à des fins de production d'énergie. Elles comprennent les espèces herbacées récoltées annuellement telles que les miscanthus ou le panic érigé et les taillis à très courtes rotations dont on récolte les rejets de souche tous les deux ou trois ans comme le saule ou le peuplier [7]. L'exploitation de ces dernières (le saule et le peuplier) représentent une option intéressante, cependant leurs méthodes de production sont encore à l'échelle expérimentale au Canada [22].

Le bois mort : les arbres (ou parties des arbres) morts à cause des perturbations naturelles telles que les épidémies d'insectes, les inondations, les foudres, les incendies, etc. pourraient également être utilisés pour la génération de produits à valeur énergétique. Dans l'Est du Canada (principalement dans la forêt boréale), les deux principaux types de perturbations naturelles sont

les incendies de forêt et les épidémies de la tordeuse des bourgeons de l'épinette. Suite aux incendies, les arbres morts sont généralement laissés debout et leur bois commence à sécher [23]. La tordeuse des bourgeons de l'épinette est reconnue comme l'un des insectes indigènes les plus destructeurs dans les forêts du nord de l'est du Canada [24]. Dans l'Ouest du Canada et surtout en Colombie-Britannique, le dendroctone du pin ponderosa crée une crise pour l'industrie forestière. Environ 10 millions d'hectares sont actuellement touchés dans cette province. Certaines parties de l'Alberta ont également été attaquées [25].

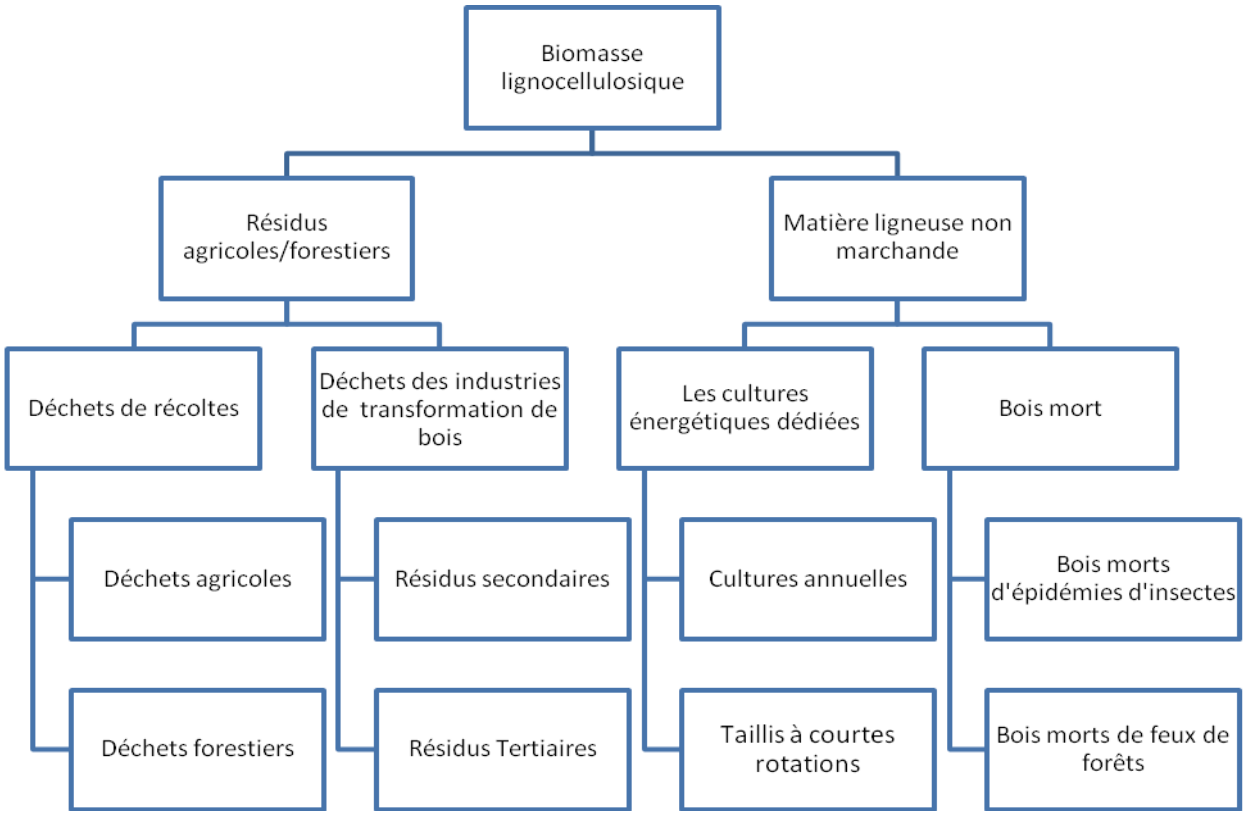

Figure 2-3: Sources de la biomasse lignocellulosique

2.6 Approvisionnement en matières premières

2.6.1 Procédés de récolte de bois

Il existe trois principaux procédés de récolte de bois qui se différencient par le degré de transformation que subit l'arbre lors de la coupe:

2.6.1.1 Le procédé de récolte de bois par arbre entier

Il consiste à abattre les arbres sur le parterre de coupe et à les débarder avec leurs branches jusqu'au bord de la route où ils vont ensuite être façonnés (généralement ébranchés). Les troncs obtenus peuvent être tronçonnés avant d'être transportés vers les lieux d'exploitation [26]. Au Canada environ 90% de la récolte de bois se fait par le procédé par arbre entier [27].

2.6.1.2 Le procédé de récolte de bois par tronc entier

En forêts des résineux, le procédé de récolte par tronc entier consiste à abattre les arbres et à les ébrancher sur le parterre de coupe. Les grumes sont ainsi débardées jusqu'au bord de la route où elles sont transportées vers le lieu d'utilisation. En forêts de feuillus, l'ébranchage est remplacé par l'écimage qui consiste à couper la cime et les branches des arbres [26].

2.6.1.3 Procédé de récolte de bois par bois tronçonnés

Il s'agit d'abattre les arbres, de les ébrancher et de les tronçonner sur le parterre de coupe, au cours d'une même opération ou au cours d'opérations successives. Les billes sont ensuite débardées jusqu'au bord du chemin forestier où elles sont transportées vers le lieu de stockage ou d'utilisation [26].

2.6.2 Procédés de récupération de la biomasse résiduelle

La biomasse résiduelle provenant de la récolte du bois est coûteuse comparativement aux sous-produits de scieries. En effet, sa faible densité entraîne des coûts de débardage et de transport élevés. Pour augmenter la masse volumique de cette biomasse résiduelle et par la suite diminuer son coût de transport, des procédés de fragmentation et de compaction ont été développés.

2.6.2.1 Fragmentation (broyage ou déchiquetage)

La fragmentation de la biomasse résiduelle en plaquettes forestières s'obtient par déchiquetage ou par broyage. Le déchiquetage est effectué avec une déchiqueteuse munie de couteaux rotatifs. Le broyage est effectué à l'aide d'un broyeur à marteaux et enclumes qui défibrent la biomasse de façon à obtenir des lamelles effilochées. La granulométrie résultant de l'usage d'une

déchiqueteuse est beaucoup plus homogène que celle obtenue à l'aide d'un broyeur [14]. Cependant, le broyeur permet de traiter la biomasse contaminée ainsi que plusieurs formes de matière lignocellulosique (résidus de coupe, fagots, troncs de bois mort) [28].

2.6.2.2 **Mise en fagots**

Dans ce procédé, la biomasse résiduelle est compressée et attachée à l'aide d'une fagoteuse sous forme de fagots. Une tronçonneuse coupe ensuite les fagots à la longueur désirée [14].

2.7 Gestion de la chaîne logistique

Une chaîne logistique représente l'ensemble des flux matériels, informationnels, financiers et tous les processus de mise à disposition de l'entreprise. Elle comprend quatre entités principales à savoir : l'approvisionnement, la production, la distribution et la vente. Une représentation de la chaîne logistique est donnée à la Figure 2-4 [29]. Chaque niveau de la chaîne peut comprendre de nombreuses installations [29]. Ainsi, la complexité de la chaîne logistique découle du nombre d'entités et du nombre d'installations de chaque entité [29].

La gestion de la chaîne logistique est définie comme l'ensemble des outils, techniques et méthodes permettant la coordination, l'intégration et la planification des différents flux et activités du réseau logistique [30]. Le principal enjeu de la gestion de la chaîne logistique est d'assurer une maîtrise optimale des coûts et de la qualité tout en minimisant les délais de livraison. La gestion de la chaîne logistique est divisée selon trois niveaux : stratégique (long terme), tactique (moyen terme) ou opérationnel (court terme).

La planification stratégique est définie comme un processus de décision à long terme traitant les choix reliés à la structure et la configuration de la chaîne logistique. Les décisions reliées à la planification stratégique du réseau concernent le nombre d'entités physiques constituant la chaîne logistique, le rôle de chaque entité (stockage, production, distribution, etc.) ainsi que sa localisation et sa capacité. La planification stratégique définit également l'acheminement des flux de matières à travers le réseau logistique ainsi que les marchés visés (produits, technologies, etc.). Les décisions prises au niveau stratégique possèdent donc un impact majeur sur les profits à long terme de l'entreprise et sur sa compétitivité. La plupart du temps, l'objectif des décisions prises au

niveau stratégique est de nature économique. Il s'agit soit de maximiser les bénéfices, soit de minimiser les coûts, tout en respectant la demande des clients et les contraintes reliées.

Les décisions fixées au niveau stratégique deviennent des orientations pour les décisions tactiques qui considèrent des données spécifiques et non prévues. La planification opérationnelle consiste à piloter l'approvisionnement, la production et la distribution dans le cadre de décisions fixées au niveau tactique.

Le développement de modèles mathématiques de planification stratégique vise à utiliser l'information disponible pour supporter la prise de décision. Ces modèles permettent d'explorer et d'analyser divers scénarios stratégiques au niveau de chaque entité de la chaîne logistique, afin de prédire les différentes actions capables d'optimiser les performances (généralement économique) de l'entreprise.

En réponse aux préoccupations environnementales, plus d'intérêt a été accordé à la gestion durable des chaînes logistiques définie comme l'intégration des objectifs environnementaux dans le planification stratégique de la chaîne logistique et dans la coordination des processus afin d'améliorer le rendement économique à long terme de l'entreprise ainsi que son impact environnemental. Un élément important dans la conception et l'analyse environnementales de la chaîne logistique est l'établissement des indicateurs de performances appropriés. Ces indicateurs sont utilisés pour concevoir les chaînes logistiques, en déterminant les valeurs des variables de décision qui donnent les niveaux de performance les plus souhaitables [31]. Ils permettent également de déterminer l'efficacité d'un réseau logistique existant ou de comparer des alternatives concurrentes. L'analyse du cycle de vie (ACV) peut être considérée comme le principal instrument de gestion environnementale de la chaîne logistique [32].

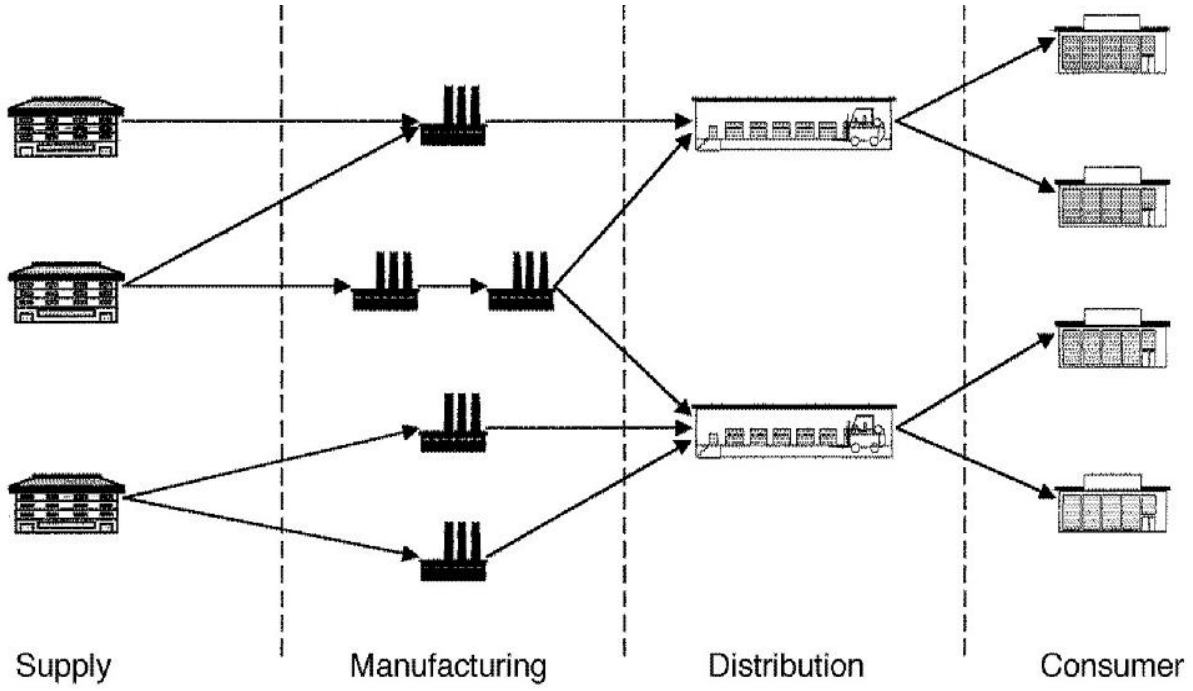

Figure 2-4: Les principales entités de la chaîne logistique

2.8 Optimisation mathématique à objectifs multiples

2.8.1 Le principe de l'optimisation à objectifs multiples

Un problème d'optimisation multiobjectif consiste à optimiser (maximiser ou minimiser) *n* critères correspondants à *n* fonctions objectifs f_k $(f(x) = f_1(x), \ldots f_k(x) \ldots\ldots, f_n(x), k = 1 \ldots n$ et *x* un vecteur de *m* variables dans un espace U à *n* dimensions) soumises à un ensemble de contraintes [33]. Dans un problème multiobjectif, il n'existe pas de solution unique, mais un ensemble de solutions appelé ensemble de Pareto (front de Pareto). L'ensemble de Pareto est définit comme un ensemble de solutions telles que pour chacune d'entre elle, toute amélioration d'un critère se traduit par la dégradation d'au moins un autre [33]. L'allure du front de Pareto prend des formes différentes en fonction du type de problème à optimiser [34] (Figure 2-5).

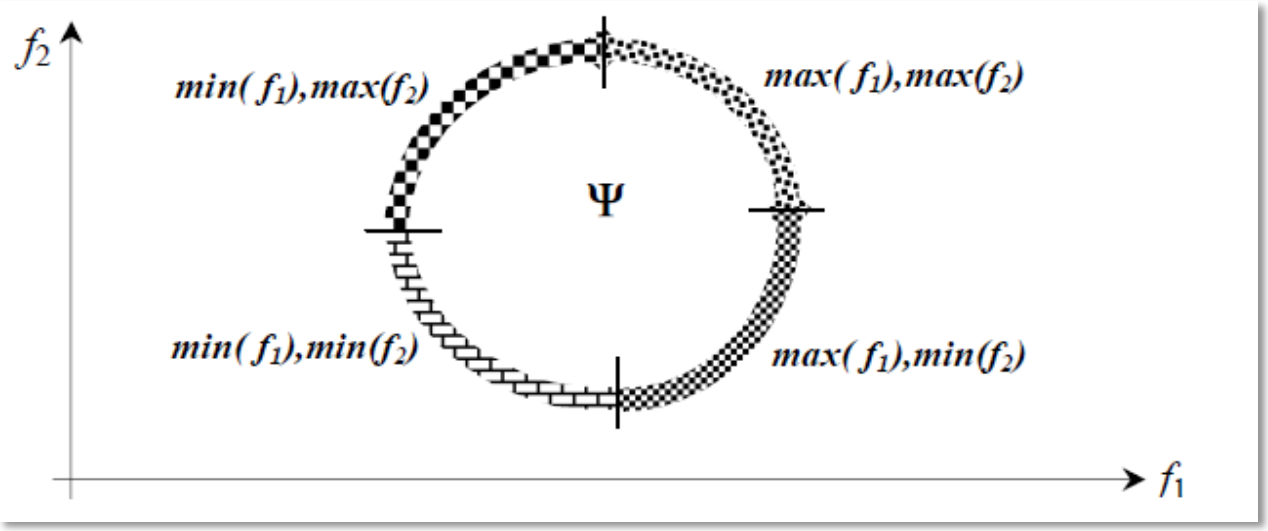

Figure 2-5: Allure du front de Pareto pour un problème à deux objectifs

2.8.2 **Les méthodes de résolution des problèmes d'optimisation à objectifs multiples**

Plusieurs approches sont capables de résoudre les problèmes d'optimisation multiobjectif à savoir les approches agrégées et les approches non agrégées.

Les méthodes agrégées consistent à transformer un problème multiobjectif en un problème monocritère. Parmi ces techniques se trouvent la méthode de la somme pondérée, la méthode du but à atteindre, la méthode de la contrainte ϵ (du compromis), etc.

La méthode de la somme pondérée consiste à définir une fonction mono-objectif *F(x)* comme la somme pondérée de toutes des fonctions objectifs *fi*. Cette approche est simple, cependant la difficulté réside dans la détermination des coefficients de pondération, reflétant les poids des objectifs, et dans la modélisation des interactions entre les différents critères [33].

Dans la méthode du but à atteindre, le décideur doit définir un but T_i qu'il désire atteindre pour chaque fonction objectif f_i. Ces valeurs sont introduites dans la formulation du problème comme des contraintes le transformant ainsi en un modèle mono-objectif. La difficulté de la méthode réside dans la mise en œuvre des buts T_i [33].

La méthode de la contrainte ϵ consiste à optimiser une seule fonction f_i en convertissant toutes les autres f_j ($j \neq i$) en contraintes, c'est à dire en considérant toute fonction f_j inferieure à une

constante $\epsilon_{j..}$Les intervalles appropriés pour les valeurs de ϵ_j doivent être déterminés au préalable pour tous les objectifs [33].

Le point commun entre toutes ces approches est l'intervention du décideur a priori (dès le début de la définition du problème) pour définir le compromis qu'il désire réaliser afin de transformer le problème multiobjectif en un problème monocritère. Ceci se concrétise soit à travers les poids affectés, les buts à atteindre ou les valeurs des ϵi [33].

Les méthodes non agrégées conduisent directement à l'obtention de l'ensemble de Pareto sans transformation du problème multiobjectif en un problème simple [33]. Parmi les méthodes non agrégées, on trouve la méthode VEGA (Vector Evaluated Genetic Algorithm), la méthode NSGA (Non-Dominated Sorting Genetic Algorithm), la méthode NSGA II, etc. Le principal inconvénient des méthodes non agrégées est qu'elles sont des approches heuristiques. Elles ne garantissent donc pas l'optimalité mais cherchent des solutions satisfaisantes approchées de l'optimum global contrairement aux procédures agrégées qui sont des méthodes déterministes. De plus, leurs conditions de convergence ne sont pas maitrisées et donc les temps de calcul sont importants [33].

2.9 Analyse de cycle de vie

2.9.1 Principe de l'analyse de cycle de vie

L'analyse de cycle de vie (ACV) est un outil méthodologique d'aide à la décision utilisé pour évaluer d'une manière exhaustive les différentes formes d'impacts environnementaux associés à un procédé ou à un produit. Elle s'applique au cycle de vie du produit depuis l'extraction de la matière première jusqu'à son recyclage ou son élimination [35].

2.9.2 Étapes de l'ACV

Selon la norme ISO 14040, L'analyse de cycle de vie se fait en quatre étapes présentées sur la Figure 2-6.

La première étape consiste à définir les objectifs de l'étude, à savoir l'application envisagée (amélioration du produit/service, comparaison du produit/service, communication), le public concerné, la méthodologie, les hypothèses (contexte géographique spécifique, scénario...), etc. Il

s'agit aussi de déterminer le champ de l'étude qui comprend la définition du système de produits à étudier, les frontières du système, ses fonctions principales et secondaires, l'unité fonctionnelle[1], les flux de référence[2], les paramètres-clés[3], etc.

Il faut noter que la comparaison des produits ou des services doit se faire sur la base d'une même unité fonctionnelle.

L'analyse de l'inventaire des ressources et des émissions constitue la deuxième étape de l'ACV. Il s'agit de calculer tous les échanges entre le système de produits et l'environnement, appelés flux élémentaires. Le but de cette étape est de déterminer les quantités des substances polluantes émises ou des ressources requises lors des différentes phases du cycle de vie du produit [33].

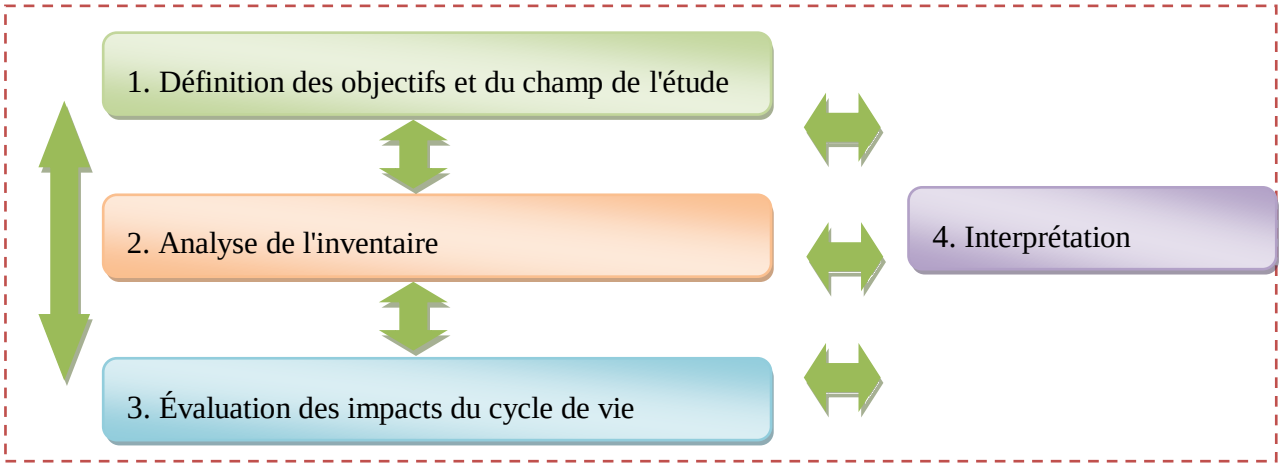

Figure 2-6: Étapes de l'analyse de cycle de vie

1 Unité fonctionnelle: C'est l'unité de quantification de la fonction d'un produit. C'est à partir de l'unité fonctionnelle qu'il sera possible de comparer des scénarios de produits

2 Flux de référence: Ce sont les quantités de produits/services nécessaires pour remplir la fonction telle que quantifiée par l'unité fonctionnelle

3 Paramètres-clés: Quantités nécessaires pour calculer les flux de référence à partir de l'unité fonctionnelle. Exemples: Durée de vie, Nombre de réutilisations possibles, Quantité de matière/d'énergie utilisée par unité de service rendu

La troisième étape met en perspective les données de l'inventaire afin d'évaluer les impacts environnementaux qui en résultent. Cette étape se déroule en deux phases :

- La phase de classification détermine les catégories d'impacts correspondant aux différents flux de l'inventaire. On identifie généralement deux types de catégories d'impacts : les catégories d'impacts intermédiaires et dommages (Figure 2-7). L'objectif de la classification est la diminution du nombre de critères dans la prise de décision.

- La phase de caractérisation permet, à travers un processus de pondération, de passer des unités d'émission de polluants ou d'extraction de ressources à des unités d'impacts pour chaque catégorie. Premièrement, la caractérisation intermédiaire fournit un score d'impact, souvent exprimé en kilogramme équivalent d'une substance polluante de référence. Ensuite, la caractérisation des dommages convertit les différents impacts intermédiaires en des dommages causés à l'environnement.

La dernière étape consiste à interpréter les résultats obtenus. Il s'agit, dans un premier lieu, de les structurer afin de déterminer les points significatifs, conformément à la définition de l'objectif et du champ de l'étude. Il convient, par la suite, d'établir et de renforcer la confiance dans les résultats à travers une étape de vérification. Finalement, il sera possible de tirer des conclusions et des recommandations.

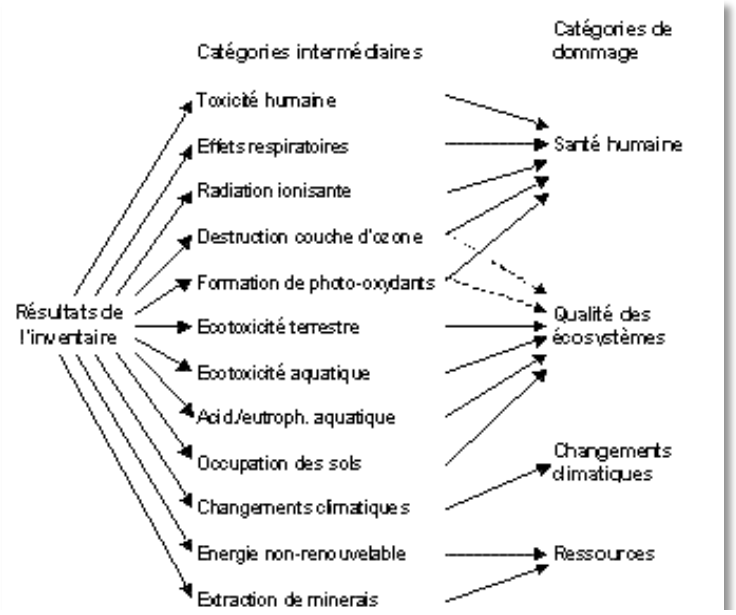

Figure 2-7: Catégories d'impacts intermédiaires et dommages de la méthode Impact 2002+

2.10 **Synthèse de la revue de la littérature**

Étant donné que la gazéification de la biomasse est une technologie encore peu utilisée, pas beaucoup d'auteurs ont travaillé jusqu'ici sur l'optimisation multicritère de la chaîne de valeur des unités de gazéification dans un contexte de bioraffinerie forestière intégrée et verte. Les études bibliographiques portent plutôt sur le développement des paramètres réactionnels du procédé de gazéification et de conversion ou sur le concept général de la bioraffinerie de gazéification.

Dans l'étude réalisée en 2008 par Leduc et al. [36], un modèle de programmation mathématique a été développé pour optimiser la chaîne de valeur des bioraffineries de méthanol en Autriche. Les résultats ont montré que l'Autriche pourrait satisfaire ses besoins en méthanol pour des mélanges de carburants en utilisant jusqu'à 8 % des terres arables. Les bioraffineries optimales proposées pourraient produire du méthanol à un coût optimal de 0,4 Euro par litre.

Une étude similaire a été menée plus tard par Natarajan et al. en Finlande [37]. La possibilité de valoriser le syngaz en méthanol, en électricité et en chaleur (système de cogénération) a été évaluée. Les résultats démontrent que le méthanol peut être produit dans l'Est du Finlande à un coût optimal de 0,34 Euro par litre (0,22 Euro par litre en valorisant la chaleur produite). L'étude a montré également que la mise en place de politiques énergétiques, telles que la tarification du CO_2 émis, a une influence sur la configuration optimale de la bioraffinerie. Ainsi le recyclage du syngaz pour la production du méthanol est plus intéressant que sa valorisation par cogénération lorsque la valeur monétaire du CO_2 dépasse 145 euro la tonne. La principale limitation de ces travaux est la conception de la bioraffinerie de gazéification en tenant compte d'une seule alternative de produit, d'une seule matière première (principalement de la biomasse agricole) et uniquement de l'aspect économique.

Plus récemment en 2010, Biagini et al. [38] ont proposé une méthode d'optimisation mathématique pour déterminer les paramètres optimaux de divers procédés de production de l'hydrogène. Différentes configurations ont été examinées à savoir la gazéification, la combustion, l'électrolyse et la séparation membranaire. Les résultats du modèle montrent que la production d'hydrogène est maximisée en utilisant un procédé de gazéification combiné à un procédé de séparation membranaire. L'approche développée par Biagini et al. ne s'intéresse pas à

la conception de la chaîne de valeur de la bioraffinerie d'hydrogène mais à l'optimisation de ses paramètres réactionnels afin de minimiser le coût de production du procédé.

Au cours de la même année, un modèle d'optimisation mathématique a été développé par Parker et al. [39] pour évaluer l'offre potentielle de divers biocarburants (esters méthyliques d'acide gras, diésel à partir des lipides, gazoline à partir de la pyrolyse d'huiles, éthanol par fermentation) à partir des biomasses agricoles et forestières, des déchets urbains et des cultures énergétiques. Les résultats démontrent qu'à un prix de biocarburant fixé à 19,6 $ par GJ, la production totale pourrait atteindre les 931 PJ, quantité capable d'alimenter jusqu'à 15 % de la demande de l'Ouest des États Unis en biocarburants. Bien que les approches de modélisation et d'optimisation de la chaîne de valeur aient été adoptées dans cette étude, cependant elles ont été employées pour la conception des bioraffineries utilisant des technologies de première génération mis à part la pyrolyse pour la production de la gazoline. De plus, l'aspect environnemental n'a pas été considéré dans ces travaux.

You et al. [40] ont été les premiers à effectuer une étude d'optimisation multicritère en considérant à la fois l'aspect économique, environnemental et social. Ils se sont intéressés à la conception et à la planification de la chaîne de valeur de la bioraffinerie d'éthanol cellulosique. L'approche proposée est illustrée par deux études de cas dans l'état de l'Illinois aux États Unis. Ces travaux, bien qu'intéressants, ne concernent la valorisation que d'un seul produit de première génération (éthanol issu de la fermentation de la biomasse de première génération) et ne permettent pas donc de comparer plusieurs alternatives de bioraffinage.

Plus tard en 2012, Gebreslassie et al. [41] ont étudié la possibilité de minimiser simultanément les coûts de production et le risque financier des bioraffineries d'hydrocarbures (diésel, gazoline, kérosène). Ils ont utilisé un algorithme stochastique multicritère et multipériode pour satisfaire les deux critères. Le modèle détermine les technologies de production, la planification de la production et les décisions de gestion de la chaîne logistique. Il a été appliqué au même cas d'étude de You et al. [40]. La principale limitation de ces travaux est que le critère environnemental n'a pas été pris en considération comme dans d'autres études citées précédemment.

Une approche similaire à celle développée par Biagini et al. [38] a été proposée par Wang and al. en 2013 [42], tout en considérant dans ce cas l'aspect environnemental. Leur modèle mathématique étudie plusieurs configurations de production de diésel à partir de la technologie FT, à savoir la gazéification à haute ou à basse température, le refroidissement direct ou indirect du gaz de synthèse, l'utilisation de catalyseur à base de cobalt, de fer ou de nickel, etc. L'optimisation de ce modèle détermine les technologies, les conditions opératoires, la consommation énergétique, la performance économique et les tailles des équipements de production d'hydrocarbures optimaux. L'analyse des résultats démontre que la gazéification de la biomasse à haute température suivie par le refroidissement direct et la production d'hydrogène en utilisant le cobalt maximisent les performances environnementales et économiques.

Wetterlund et al. [2] ont été les premiers à étudier l'impact de l'intégration des unités de gazéification de la biomasse dans les usines papetières suédoises. Deux alternatives ont été considérées: la production du dimethyl éther (DME) et la cogénération. Les performances économiques, environnementales ainsi qu'énergétiques de la bioraffinerie ont été estimées et comparées aux performances de l'usine de P&P réceptrice.

Jonsson et al. [43] ont analysé en 2012 différentes options de production de vapeur lorsque la capacité de l'usine de pâte kraft augmente de 25 %. Les options envisagées comprennent l'extraction de la lignine, la gazéification de la liqueur noire avec la valorisation du syngaz en électricité ou en DME et le remplacement de la chaudière de récupération. Ces options ont été comparées d'un aspect économique et environnemental pour différents scénarios du marché de l'énergie.

Seules les deux dernières études portent sur l'intégration des unités de gazéification dans les usines papetières. Cependant, ces travaux ne s'intéressent pas à l'optimisation de la chaîne de valeur de la bioraffinerie de gazéification intégrée, il s'agit seulement de comparer des alternatives d'utilisation du syngaz dans un tel contexte. De plus, l'approche utilisée pour estimer les émissions environnementales n'est pas systémique et ne permet pas de considérer les relations et échanges entre les différents composants du système à l'étude.

Une synthèse de la revue de la littérature est présentée dans le Table A-1 de l'annexe A.

CHAPITRE 3 APPROCHE MÉTHODOLOGIQUE

3.1 Objectif général

Optimiser la chaîne de valeur des bioraffineries de gazéification intégrées dans les usines de pâtes et papiers canadiennes afin de déterminer la configuration optimale des BRFIV de deuxième génération.

3.2 Objectifs spécifiques

Les objectifs spécifiques qui vont aider à atteindre l'objectif principal sont les suivants:

a. Identifier les sources de biomasse compatibles par rapport à une valorisation thermochimique.

b. Identifier les alternatives produits/procédés appropriées pour une valorisation par gazéification de la biomasse lignocellulosique en bioproduits.

c. Comparer la faisabilité économique des alternatives produits/procédés intégrées dans un concept de BRFIV.

d. Déterminer les impacts environnementaux relatifs aux alternatives produits/procédés retenues ainsi qu'aux différents scénarios d'approvisionnement en biomasse lignocellulosique sélectionnés.

e. Optimiser la chaîne de valeur de la bioraffinerie de gazéification intégrée aux usines de P&P d'un point de vue économique.

f. Développer des configurations optimales de la bioraffinerie de gazéification intégrée dans l'Est et l'Ouest du Canada en considérant les critères économiques et environnementaux.

3.3 Hypothèse

La conception optimale de la chaîne logistique des bioraffineries de gazéification intégrées dans les usines papetières canadiennes assure la rentabilité économique et la viabilité environnementale de ce complexe.

3.4 **Méthodologie**

Afin d'atteindre les objectifs spécifiques fixés, la méthodologie de la Figure 3-1 a été proposée.

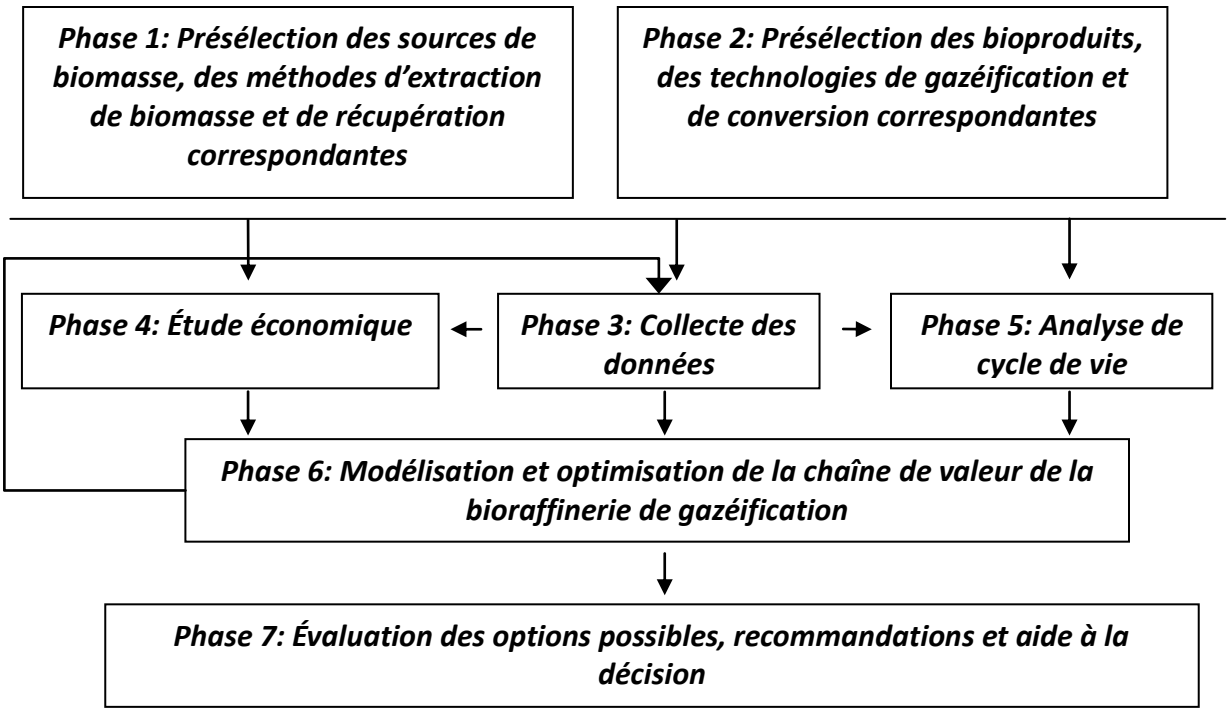

Figure 3-1: Méthodologie globale

3.4.1 **Phase 1 : Présélection des sources de biomasse**

Les sources de biomasse sont sélectionnées selon leurs propriétés physiques et chimiques. En effet, dépendamment de ces caractéristiques, la composition du syngaz en termes de CO, H_2, CO et CH_4 ainsi qu'en termes d'impuretés (H_2S, NH_3, cendres) à la sortie du gazéificateur change [44]. Les principales caractéristiques physico-chimiques influençant la réaction de gazéification sont : la teneur de la biomasse en polysaccharides et en lignine, le taux d'humidité, la teneur en cendres ainsi que la teneur en soufre et en azote.

La composition chimique de la biomasse lignocellulosique en polysaccharides (cellulose, hémicelluloses) et lignine varie. Il s'agit d'une caractéristique importante pour la conversion thermochimique par gazéification [44]. Une teneur élevée en lignine dans la biomasse destinée à la gazéification n'est pas souhaitée puisque le taux de conversion de carbone dans ce cas est plus

faible [45]. À ce niveau, l'utilisation des résidus de coupe, des sciures, des copeaux et du bois mort d'épidémies d'insectes est la plus adéquate. En effet, les sciures, les coupeaux et les résidus de coupe présentent une teneur plus élevée en polysaccharides et un plus faible pourcentage en lignine par rapport à l'écorce et le bois mort d'incendies de forêts. Le bois mort d'épidémies d'insectes est principalement attaqué par des champignons qui décomposent en grande partie la lignine et les hémicelluloses et gardent intacte la cellulose.

Le taux d'humidité influence d'une manière significative le rendement énergétique du procédé de gazéification. Pour un taux d'humidité dépassant les 15%, il ne faut pas passer par une étape de séchage avant la gazéification. Plus la biomasse est humide, plus on va dépenser de l'énergie pour la sécher avant de l'introduire dans le gazéificateur [46]. La faible teneur en eau est sans doute l'avantage le plus important associé à l'utilisation des arbres morts (30 % après 2 mois et 20% après un an) [23] comparativement aux résidus de coupe et de sciage dont le taux d'humidité est plus élevé (50-60%) [47].

Les cendres sont les éléments non combustibles de la biomasse. Une teneur élevée en cendres réduit l'efficacité de conversion du gazéificateur puisqu'on les retrouve directement dans le gaz de synthèse. D'autre part, une forte teneur en cendres dans le syngaz donne lieu à des problèmes d'encrassement et de formation de mâchefer (utilisation du syngaz dans des chaudières). Sa présence en quantité importante complique également la manutention des équipements en aval et diminue le rendement énergétique du procédé (plus de nettoyage) [46].

C'est au niveau de la teneur en cendres que les biocombustibles se distinguent le plus. Le bois contient généralement moins de 0,5 %. L'écorce en renferme entre 1 et 3% [47]. Les résidus de coupe comportent du bois en plus des écorces, ils présentent donc une teneur en cendres légèrement inférieure aux écorces. Les sciures et les copeaux issus des déchets de scieries ne comportent pas d'écorces. La teneur en cendres des sciures varient entre 0,5 et 2% et celle des copeaux entre 0,4 et 0,5% [47]. Ces sources améliorent ainsi la qualité de la biomasse destinée à la gazéification [46]. Les arbres morts perdent souvent leur écorce, ils ont une teneur en cendres qui se situe entre 0,25 et 0,3% selon le niveau de dégradation (pourriture) de l'arbre. Toutefois, les grandes quantités de charbon trouvées sur les troncs des arbres détruits par le feu augmentent la teneur en cendres de la matière et peuvent ainsi limiter les avantages réels de l'absence d'écorce [23].

La gazéification de la biomasse contenant du soufre et de l'azote génère du sulfure d'hydrogène (H_2S) et de l'ammoniac (NH_3). Ces contaminants se présentent comme des poisons pour certains catalyseurs utilisés lors de la conversion catalytique du syngaz en bioproduits (à base de fer, de cobalt, de zinc, etc.) et peuvent conduire à leur désactivation. De plus, l'ammoniac est corrosif pour certains matériaux tels que le cuivre et le zinc. L'élimination de ces contaminants est donc primordiale [46]. La plupart des déchets de biomasse (sciures, copeaux, résidus de coupe) présente une faible teneur en soufre (moins de 0,05%) [47]. Le taux d'azote se situe entre 0,1 et 0,5% pour les déchets de scieries (à part les écorces) et entre 0,3 et 0,5% pour les résidus de coupe [47]. Concernant les arbres morts, la teneur en azote varie au cours du temps. Généralement, juste après la mort de l'arbre, le contenu en NH_3 diminue. Il augmente considérablement après que les arbres sont tombés au sol (0.44% lorsque la pourriture est répandue dans l'arbre). Par conséquent, l'utilisation des arbres morts, encore debout, est plus avantageux [46].

En se basant sur ces critères, trois sources de biomasse lignocellulosique ont été sélectionnées à savoir: les résidus de coupe, le bois mort ainsi que les déchets de scieries. Les options des déchets agricoles et des cultures énergétiques sont cependant écartées étant donné qu'elles ne satisfont pas l'ensemble des critères.

3.4.2 **Phase 2 : Présélection des bioproduits et des technologies de gazéification et de conversion correspondantes**

– Phase 2.1: Identification des bioproduits valorisables à partir du gaz de synthèse

Pour atteindre l'objectif de la phase 2.1, il faut au préalable effectuer une revue de littérature détaillée des voies de valorisation possibles du gaz de synthèse. Il convient dans une seconde étape d'identifier des critères de sélection pour choisir les produits les plus avantageux à inclure dans la chaîne de valeur de la bioraffinerie de gazéification.

Les critères de sélection des produits choisis sont de natures :

- techniques : maturité de la technologie, similitude au procédé pétrochimique
- économiques : tailles des marchés actuels et futurs des produits issus du syngaz

- utilisation du produit final : compatibilité avec l'infrastructure mise en place (pour les biocarburants).

En se basant sur ces critères, 4 produits valorisables à partir du syngaz ont été retenus à savoir le diésel F-T, le méthanol, l'ammoniac et l'éthanol.

– Phase 2.2: Identification de la meilleure configuration de gazéification pour chaque produit retenu

Il s'agit dans cette phase d'analyser des différentes technologies de gazéification et de purification disponibles dans la littérature et d'identifier des critères de sélection pour choisir la configuration la plus appropriée à chaque produit présélectionné.

Le choix du gazéificateur est guidé par la nature de la matière lignocellulosique utilisée, la taille de l'installation, l'usage du gaz de synthèse (en termes du pouvoir calorifique exigé et de la teneur tolérée en impuretés du produit final), l'investissement mis en jeu et enfin la complexité technologique.

Les critères de flexibilité de la technologie vis à vis du type de la biomasse et sa capacité maximale écartent l'option d'utiliser des réacteurs à lit fixe dans cette étude. En effet, ces derniers sont rarement utilisés pour gazéifier la biomasse, leur production est limitée à environ 10 MW et ne sont donc pas compatibles aux unités à l'échelle industrielle. Les procédés à lit fluidisé sont cependant prouvés pour la gazéification de la biomasse, offrent une plus grande flexibilité vis à vis du type de la matière première en termes de densité, de taille et de composition, de plus, ils peuvent être utilisés dans des installations à grande échelle (plus de 100 MW). Le gazéificateur à lit fluidisé a donc été retenu pour toutes les alternatives de produits présélectionnées.

Le critère lié à l'usage du produit final (l'adéquation de la technologie de gazéification avec le produit final) élimine l'option d'utiliser de l'air dans le réacteur de gazéification à lit fluidisé puisqu'il conduit à la formation d'un gaz de synthèse de faible pouvoir calorifique (PC), entre 4 et 8 MJ/Nm^3. Ce dernier peut être utilisé pour la production de l'électricité et de la chaleur dans un cycle combiné ou pour la valorisation dans des chaudières. Les gazéificateurs, utilisant des mélanges d'oxygène et de vapeur d’eau, permettent d’augmenter le PC du gaz produit [48]. Ils s'adaptent bien aux systèmes de production des produits chimiques et des biocarburants. Ainsi,

pour la formation de l'ammoniac, du méthanol, du diésel F-T et de l'éthanol, le choix de l'oxydant s'est fixé sur le mélange d'oxygène et de vapeur d'eau.

L'utilisation d'un gazéificateur pressurisé à lit fluidisé permet de satisfaire le troisième critère lié à l'investissement mis en jeu. En effet, avec cette configuration, il ne sera plus nécessaire de comprimer le gaz de synthèse avant les réactions du gaz à l'eau (ajustement du ratio H_2/CO) et les réactions de synthèse de carburants. Les gazéificateurs pressurisés assurent, ainsi, un gain énergétique important réduisant l'investissement et les coûts opératoires requis [11].

Il est à noter que la configuration à lit entraîné n'a pas été sélectionnée, dans cette étude, à cause des exigences élevées de prétraitement de la biomasse (granulométrie très fine de l'ordre de 100 à 600 microns [15]), des besoins énergétiques importants pour atteindre les températures du lit ainsi que la complexité dans la conception et le fonctionnement de ce type de réacteur [3].

En se basant sur ces critères, le gazéificateur pressurisé à lit fluidisé alimenté à l'oxygène et à la vapeur d'eau développée par l'institut 'Gas Technology Institute' a été retenu.

3.4.3 **Phase 3 : Collecte des données**

Trois types de données sont requis pour la réalisation des phases 4, 5 et 6 de ce projet de doctorat.

Les données techniques comportent les propriétés des sources de biomasse sélectionnées (densité et taux d'humidité), les bilans de masse et d'énergie des procédés de conversion retenus (gazéification, nettoyage, conditionnement et conversion), les productivités et les consommations (en termes de carburant, d'électricité et de lubrifiants) des différents systèmes de récolte de bois et de traitement des déchets, etc. Des modèles de simulation des procédés de gazéification et de conversion du gaz de synthèse en méthanol et en diesel F-T ont été développés en utilisant le logiciel Aspen Plus afin d’obtenir les bilans de masse et d'énergie, les besoins en eau et en produits chimiques ainsi que la productivité de chaque procédé.

Les données économiques contiennent les investissements et les coûts opératoires des technologies de conversion des produits, les coûts des différentes méthodes de récolte et de traitement de la biomasse, les coûts d'achats des déchets de scieries, etc.

Enfin, les données spatiales incluent les paramètres du modèle d'optimisation à savoir les emplacements des sites d'approvisionnement en biomasse et les quantités respectives, les emplacements des usines de P&P, des scieries, des industries pétrochimiques, etc.

Les quantités de biomasse disponible ont été déterminées à partir du système d'information géographique Arcgis permettant la manipulation, la gestion, l'analyse et l'édition des données spatiales.

L'ensemble des données à collecter est présenté dans le Table A-2 de l'annexe A.

3.4.4 Phase 4 : Études économiques

La rentabilité économique est un critère fondamental pour la mise en place des projets. Ces derniers doivent être donc sujets à une analyse économique. Les données bibliographiques recueillies lors de la phase 3, comportant les bilans de masse et d'énergie des procédés de gazéification et de conversion sélectionnés seront traduits en termes de coûts d'investissements, de coûts opératoires et d'indicateurs économiques. Ces derniers seront utilisés pour évaluer la rentabilité économique relative à chaque alternative de produit retenue.

3.4.5 Phase 5 : Analyse de cycle de vie

Il s'agit d'évaluer la performance environnementale de divers scénarios de chaîne logistique de la bioraffinerie de gazéification. Cette étape impose une analyse complète du cycle de vie des différents produits et procédés considérés.

La démarche à suivre consiste tout d'abord à définir la frontière de l'étude ; en d'autres termes, choisir les différentes étapes et alternatives à inclure dans la chaîne de valeur pour mener une analyse environnementale comparative sans changer significativement les conclusions générales de l'étude. La chaîne logistique comporte l'étape de récolte de bois (alternatives: procédé par arbre entier, par tronc entier, par bois tronçonné), l'étape de traitement des déchets de bois (alternatives: déchiquetage, mise en fagot), le transport de la biomasse (alternatives: déchets de bois ou bois mort sous leurs formes initiales, sous forme de copeaux, déchets de bois sous formes de bales), l'étape de conversion et enfin l'étape de distribution des bioproduits. Il convient par la suite de définir les processus élémentaires pour chaque produit/procédé à l'étude, de déterminer

les flux de référence correspondants et d'établir les étapes de processus (diagramme de flux échangés dans un système de produits).

La deuxième étape de l'ACV portera sur l'identification de l'inventaire relatif à chaque processus élémentaire de chaque étape de cycle de vie. Pour cela, des données de la littérature (phase 2 du projet) ainsi que la base de données Ecoinvent, implémentée dans le logiciel Simapro, seront utilisées. Cette base de données est généraliste ; elle contient des processus élémentaires dans divers secteurs d'activités tels que la sylviculture, l'énergie, le transport, etc., d'où l'intérêt de son utilisation.

La troisième étape consiste à traduire les résultats d'inventaire pour chaque système de produit/procédé en impacts environnementaux qui sont, dans ce cas, le changement climatique et la consommation des ressources fossiles. La méthode de caractérisation (évaluation des impacts) retenue est la méthode IMPACT 2002+ (IMPact Assessment of Chemical Toxics) [49], incluse dans le logiciel Simapro et pour laquelle on retrouve les catégories d'impacts désirées (changement climatique et consommation des ressources non renouvelables). Quoi que toutes les méthodes de caractérisation soient fondées sur des bases scientifiques communes, les différences apparaissent au niveau des types et du nombre de catégories d'impacts choisies pour chaque méthode. La méthode IMPACT 2002+ dispose de 14 catégories d'impacts intermédiaires, elles même agrégées en 4 catégories de dommages distinctes à savoir : la santé humaine, la qualité des écosystèmes, le changement climatique et l'utilisation des ressources [49-51].

3.4.6 **Phase 6 : Modélisation et optimisation de la chaîne de valeur de la bioraffinerie de gazéification**

- Phase 6.1: Traitement, préparation et stockage des données

Dans le cas où on traite un problème d'optimisation comportant un nombre de paramètres très important, il est plus judicieux d'utiliser les données d'une manière plus lisible. Il convient alors de les préparer, de les traiter et de les stocker, au préalable, en utilisant l'outil Excel. Le fichier Excel contiendra deux types de données [52]:

- Des données brutes : elles sont soit directement introduites à partir des sources de données disponibles, soit traitées (addition, moyenne, conversion d'unité…) avant la saisie dans Excel [52].
- Des données calculées: elles sont calculées à partir de données brutes. Les résultats obtenus sont utilisés directement pour la modélisation du problème mathématique. Cela permet d'alléger l'écriture du modèle et d'accélérer l'exécution [52].

- Phase 6.2: Modélisation du problème d'optimisation multicritère par un programme linéaire en nombre entier sous le logiciel GAMS (Generalized algebraic modeling system).

Il s'agit dans cette phase de formuler le problème d'optimisation, c'est à dire de traduire mathématiquement le problème en fonctions objectifs, variables de décision, paramètres et en contraintes linéaires. Le logiciel GAMS est un outil informatique de modélisation algébrique des problèmes mathématiques complexes. Il a été retenu dans ce travail parce qu'il permet une description du modèle indépendante des solutions algorithmiques et il offre la possibilité d'accéder à une variété de solveurs puissants en utilisant le même code [53].

- Phase 6.3: Optimisation multicritère de la chaîne de valeur de la bioraffinerie de gazéification intégrée.

Cette étape consiste à résoudre le modèle mathématique développé lors de la phase 6.2. Dans ce projet, le choix s'est porté sur un programme linéaire en nombre entier (PLNE) pour résoudre le problème multicritère, étant donné qu'il requiert l'introduction de variables binaires (choix ou non d'une source de biomasse, implanter ou non une bioraffinerie dans une usine de P&P donnée, etc.) et mixtes (quantités de biomasse utilisée ou de produit généré, capacité, etc.). L'utilisation de méthodes déterministes (PLNE dans ce cas) dans un cadre multicritère est possible moyennant des approches agrégées, où le problème multiobjectif est transformé en un problème mono-objectif. Le choix d'une méthode évolutionnaire (non agrégée) n'est pas judicieux car les méthodes agrégées permettent d'optimiser plusieurs objectifs avec un temps de calcul moins important, avec moins de complexité et de garantir un ensemble de solutions optimales (front de Pareto).

Le choix s'est porté sur la méthode d'optimisation multicritère epsilon-contrainte. L'idée est de minimiser/maximiser un premier objectif *F1* et de transformer le second objectif *F2* du problème en une contrainte bornée. Le choix de l'objectif à optimiser et celui à considérer comme contrainte est fait par l'utilisateur. La méthode epsilon-contrainte conduit à un ensemble de solutions possibles aussi bonnes les unes que les autres au sens de Pareto appelé front de Pareto. Dans ce cas, la fonction *F1* maximise les profits et *F2* minimise les émissions environnementales.

L'implémentation de la méthode Epsilon-contrainte se fait en deux phases:

- La première phase consiste à déterminer la borne inférieure et supérieure de *F2*. La borne inférieure est déterminée par la résolution du problème mono-objectif de minimisation des émissions des gaz à effet de serre (sans prendre en considération *F1*). La borne supérieure est fixée en optimisant la même fonction objectif *F2* en ajoutant au modèle, cette fois-ci, la contrainte de l'équation (4) :

$$Contrainte: Profit \geq \max F1 + constante \quad (4)$$

La constante prend une valeur très petite de l'ordre de 1% (1 % du profit maximal).

Il faut donc résoudre au préalable le problème monocritère de maximisation de *F1*.

- La deuxième phase de la méthode epsilon- contrainte consiste à diviser l'espace de variation de *F2* (entre la limite inférieure et la limite supérieure trouvées dans la phase 1) en de nombreuses sections pour avoir autant de solutions que de sections. On optimise ensuite *F1* pour chaque section de l'espace de variation de *F2*. Cette procédure permet de tracer le front de Pareto représentant les valeurs de *F2* en fonction de *F1*.

3.4.7 **Phase 5 : Évaluation des options possibles, recommandations et aide à la décision**

En optimisation multiobjectif, la solution optimale n'est plus une solution unique mais, un ensemble de solutions de compromis entre les différents objectifs à optimiser. Cette phase consiste à évaluer l'ensemble des solutions optimal (le front de Pareto) pour ne retenir qu'une seule solution. Une solution peut être meilleure qu'une autre sur certains objectifs et moins bonne sur d'autres. Étant donné que le critère principal à optimiser dans notre cas est le coût, les

solutions retenues dans cette étude sont celles capables de réduire au mieux les émissions de GES ou la consommation des ressources fossiles évitée (l'écart entre deux solutions par rapport à ces critères est le plus important) en augmentant minimalement le coût de production (l'écart entre deux solutions par rapport au critère économique est le plus faible). L'outil d'aide à la décision propose ainsi des recommandations (choix de la biomasse, emplacements, nombre et capacités optimaux des bioraffineries, réseau de distribution des bioproduits, etc.) en considérant les solutions de compromis retenus ainsi les solutions minimisant les coûts.

3.5 Présentation des articles et cohérences avec les objectifs de recherche

Les travaux de recherche présentés dans cette thèse sont supportés par quatre articles soumis. Le premier article évalue la faisabilité économique de l'implémentation des bioraffineries de gazéification dans les usines de pâtes et papiers dans un concept de BRFIV. L'analyse de cycle de vie de dix scénarios de chaîne logistique de la bioraffinerie de gazéification est présentée dans le deuxième article. Le troisième article porte sur l'optimisation économique de la chaîne de valeur de la bioraffinerie forestière intégrée et verte. Un outil d'aide à la décision multicritère caractérisé par un large choix de matières premières, de procédés de récupération de la biomasse résiduelle et de bioproduits issus de la gazéification est présenté dans l'article 4. Les liens entre les objectifs de recherche et les articles sont résumés dans le Table 3-1.

Tableau 3-1: Liens entre les articles et les sous-objectifs de recherche

Article	Sous-objectifs
Article 1 : Syngas Utilization in a Green Integrated Forest Biorefinery: Economic Assessment	-Identifier les alternatives produits/procédés appropriées pour une valorisation thermochimique de la biomasse lignocellulosique. -Comparer la faisabilité économique des alternatives produits/procédés intégrées dans un concept de BRFIV.
Article 2 : Life Cycle Assessment of Alternative Options for Gasification-Based Biorefinery Supply	-Identifier les sources de biomasse compatibles pour une valorisation thermochimique ainsi que leurs procédés de récupération. -Calculer les impacts environnementaux relatifs aux alternatives produits/procédés retenues ainsi qu'aux différents scénarios
Article 3: Optimal Design of an Integrated Biorefinery Supply Chain in Eastern Canada: Example of Biomethanol Production in Pulp Mills	-Optimiser la chaîne de valeur de la bioraffinerie de gazéification intégrée aux usines de P&P d'un point de vue économique.
Article 4 : Multicriteria Optimization for the Design of an Integrated Forest Biorefinery Supply Chain in Canada	-Proposer des configurations optimales de la bioraffinerie de gazéification intégrée dans l'Est et l'Ouest du Canada en considérant les critères économiques et environnementaux.

CHAPITRE 4 ARTICLE 1: SYNGAS UTILIZATION IN A GREEN INTEGRATED FOREST BIOREFINERY: ECONOMIC ASSESSMENT

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4.1 Summary

The Green Integrated Forest Biorefinery (GIFBR) is a multi-revenue generating complex composed of four units: a Kraft mill, a biorefinery unit, a biomass gasification plant and a polygeneration unit. In this study, the economic viability of the gasification unit implementation was assessed. The first case study investigates the production of syngas to substitute the fossil fuel consumed internally. The second case study includes the valorization of syngas to biofuels and biochemicals such as Fischer-Tropsch (F-T) diesel, ethanol, methanol and ammonia. At current market conditions, the implementation of the gasification unit to replace natural gas may not be economically viable. An internal rate of return (IRR) of 7 % is obtained for methanol synthesis case making it the best option compared to F-T diesel and ammonia alternatives. The

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methanol option would [2]achieve its target rate of return TRR at a methanol price 60 % higher than the actual fossil fuel price. A selling marginal price in the range of 75 % is required to reach the TRR for F-T diesel and ammonia alternatives. However, the investments costs significantly influence the IRR of the options; if the capital investments decrease by 30 %, then the options could reach the TRR with 35 %, 42 % and 49 % increase of the fossil fuel prices, respectively for methanol, F-T diesel and ammonia.

Keywords: syngas; biofuels; biochemicals; green integrated forest biorefinery; biomass; gasification; economic evaluation

4.2 Introduction

The concentration of CO_2 in the atmosphere has increased significantly since the beginning of the industrial revolution. It has grown from 280 moles of CO_2 per million moles of air in the mid-eighteen century [54] to an alarming level of 404 moles of CO_2 per million moles of air in 2016 [55]. The implementation of different measures in several domains has been investigated. The development of value added products derived from forest biomass in a green integrated forest biorefinery (GIFBR) concept could be an interesting and effective mean to contribute to the stabilization of CO_2 emissions. In addition, it could be a promising solution to dependence on fossil resources, and an opportunity for the pulp and paper (P&P) industry to broaden its portfolio of products and generate new revenues.

The GIFBR is composed of four units: a Kraft receptor mill, a biorefinery unit, a polygeneration unit, and a woody biomass gasification plant [56].This multi-revenue generating complex is characterized by low greenhouse gases (GHG) emissions and a nil fossil fuel consumption. Its water consumption is reduced. The aim of a zero fossil fuel consumption of the GIFBR is of particular interest from and environmental and economic point of view. The implementation of the gasification unit ensures a nil fossil fuel usage in the GIFBR. Furthermore, the gasification together with the subsequent conversion pathways could be an opportunity to guarantee the environmental and the economic viability of the complex.

The objective of this work is to evaluate the economic viability of syngas production to substitute fossil fuels in the Kraft process and to compare different energy-related investment options that can be implemented using the generated syngas. Two case studies have been conducted:

- The first case study assesses the economic feasibility of replacing natural gas by syngas to satisfy the internal needs of the GIFBR;
- The second case study compares the economic viability of four investment options: Fischer-Tropsch (F-T) diesel, methanol, ethanol and ammonia.

4.3 Background

4.3.1 Interest to implement a gasification unit

Biomass can be converted into biochemicals and biofuels through biochemical and thermochemical conversion processes [6]. The biochemical processes are based on the sugars platform and convert the biomass into liquid and gaseous fuels by fermentation and anaerobic

digestion, respectively. The biochemical conversion pathways are outside the scope of this study [6]. The thermochemical conversion processes are based on the syngas platform and include combustion, gasification, and pyrolysis.

Thermochemical conversion technologies have certain advantages over biochemical conversion technologies. They can convert various types of biomass (including agricultural and forestry residues, byproducts from biorefineries and food industry, organic municipal wastes, etc.) [6] to a variety of biofuels (H_2, F-T diesel, synthetic gasoline) and chemicals (methanol, ammonia) similar to petroleum derivatives and compatible with the existing petroleum refining operations [6].

Compared to combustion, gasification has a higher overall efficiency of heat and electricity generation. Furthermore, lower amounts of NO_x and other syngas contaminants are emitted since less air is required to complete the combustion of solid fuels; in addition, trace elements are removed efficiently [6].

Gasification could be the most attractive pathway to transform the P&P industry to a GIFBR and to ensure its economic and environmental viability. The use of syngas instead of natural gas to start the bark boiler operation and to fire the lime kiln could ensure low emissions of greenhouse gases of the overall GIFBR, compared to the current practice of similar facilities. Furthermore, through gasification and subsequent conversion processes, numerous syngas valorization options are possible. The use of forest biomass residues to produce biochemicals or biofuels could generate additional profits for the pulp and paper mill.

4.3.2 Description of the gasification process

The wood biomass gasification process consists of three successive steps [56]:

- Biomass drying and pre-treatment;
- Gasification;
- Cleaning and reforming of the syngas.

Due to the high moisture content of biomass, a drying stage prior to gasification is required to reduce the moisture content of the biomass from about 50 % to about 15 %. The high moisture content of feedstock decreases its performance [57]. Drying process may reduce the required heat to raise the gasifier temperature to its operating target [6] and therefore increase its overall efficiency.

Gasification is an endothermic process, it takes place at high temperature, typically between 873 K and 1273 K, in the presence of a gasifying agent (air, steam, oxygen, etc) [57]. During the gasification step, biomass is broken into lighter hydrocarbons, gases (CO, CO_2, H_2, and CH4), ash, char, tar, and minor contaminants through pyrolysis, partial oxidation and char gasification. Char and tar are produced by the incomplete conversion of biomass [6].

During gasification, particulates, tar, alkali compounds, nitrogen and sulfur contained in the biomass are reformed and transferred into the product gas. In order to prevent catalyst damage during syngas conversion, the impurities need to be removed [6]. Tolerable amounts of contaminants in the syngas depend on the syngas applications [6]. Conventional cold gas cleaning includes a baghouse or sand filter to remove solid particles and partially tars, a scrubber for removal of ammonia, metals and residual tars as well as guard beds for scavenging hydrogen sulfide. Alternatively, hot gas cleaning by particle removal with candle filters or electrostatic precipitators, thermal or catalytic cracking of the tars and high-temperature adsorption of other contaminants could be applied [57].

A reforming step is used to meet the quality requirements for the specific syngas utilization. Reforming reactions can modify the gas composition based on the desired utilization. For example, specific ratios of CO/H_2 are needed to produce fuels and chemicals from syngas [6].

4.3.3 Syngas conversion technologies

Numerous chemicals and fuels can be produced from biomass gasification, as illustrated on Fig.4-1, and four main pathways are used. The syngas from biomass gasification can be burned in boilers or lime kilns to produce heat, it can be used to produce heat and electricity using a combined heat and power system called a biomass integrated gasifier combined cycle [6]. Syngas is a building block for the synthesis of a variety of fuels (F-T diesel, gasoline, methanol, and ethanol) and chemicals (ammonia, hydrogen) via catalytic or biological conversion process. The physical and chemical properties of fuels and chemicals produced are similar to those of the fuels and chemicals derived from fossil fuels [18].

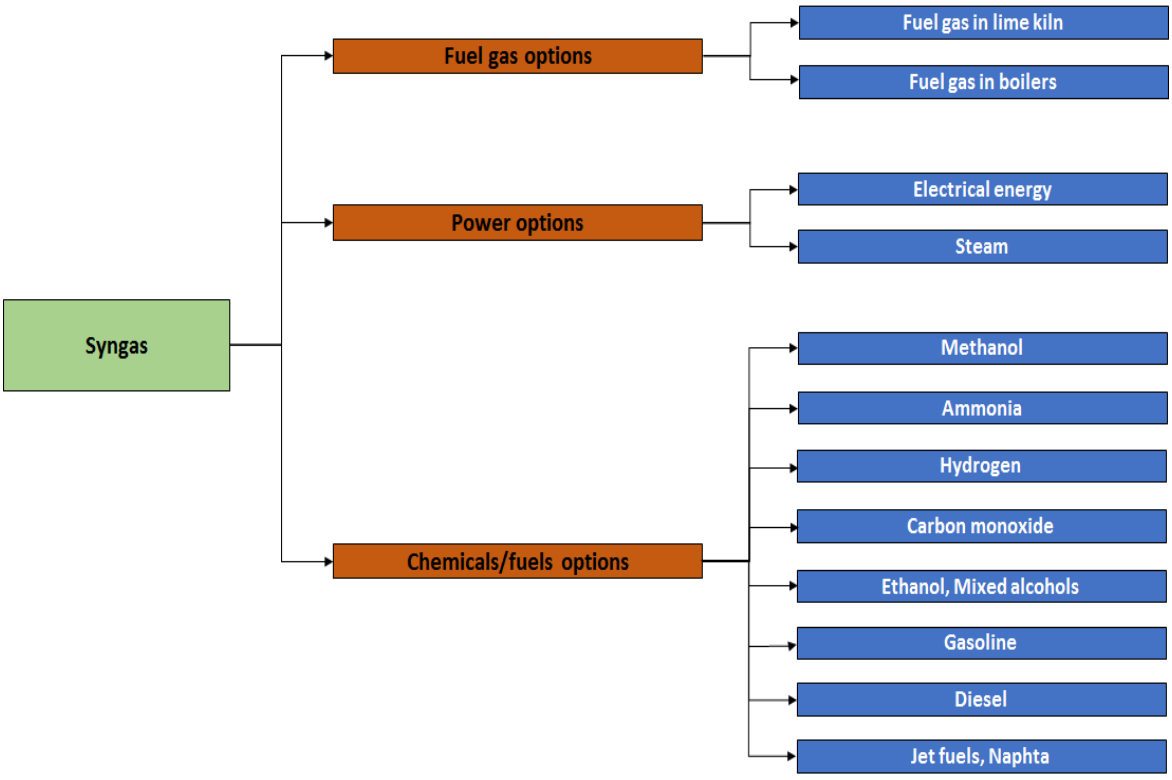

Figure 4-1: Potential products from syngas

4.4 Economic analysis of the gasification unit implemented in a P&P mill

4.4.1 Receptor mill case study

The receptor mill of the GIFBR considered in this work is an actual Kraft dissolving pulp mill located in eastern Canada. The mill uses hardwood chips to produce dissolving pulp for textile applications. The steam required by the P&P process is mainly produced by burning the black liquor in the recovery boiler. Additional steam is generated by combusting bark in a biomass boiler. The generated steam from the recovery boiler and from the bark boiler is fed to a steam turbine to provide 13.7 MW of electricity. The consumption of fossil fuel is 54 t d^{-1} (natural gas)

used to fire the lime kiln (31 t d^{-1}) and to initiate the boiler combustion (23 t d^{-1}). The main parameters of the receptor Kraft mill are given in Table A.1 in the Appendix.

4.4.2 Selection of bioproducts derived from syngas

The syngas conversion options are selected in view of the context (GIFBR with nil fossil fuel consumption, low GHG emissions and additional profits), of reference mill characteristics, available technologies for the selected bioproducts and potential final users.

In the first scenario, syngas is consumed internally. It is produced to replace the natural gas in the lime kiln, to initiate the combustion in the bark boiler of the Kraft process and to supply the steam dryer used to preheat the biomass prior to its combustion in the boiler. This objective is to ensure a nil fossil fuel consumption of the GIFBR. The proposed alternative is technically feasible with minor modification of the lime kiln operation [56]. An adjustment is required due to the lower heating value of syngas compared to natural gas (Table A.2). The biomass gasification is commercially used to produce heat by burning syngas in a boiler [18] and to fire the lime kiln [56].

The second scenario consists of producing syngas for the lime kiln, in the bark boiler and in addition, to generate biochemicals or biofuels for substitution of fossil-based products. Taking into consideration economic criteria (size of the actual and future syngas market, product market) and technical feasibility, four options are selected; F-T diesel, ethanol, methanol and ammonia. Ethanol and F-T diesel are considered as transportation fuels, while methanol and ammonia will be sold as chemical products.

The F-T diesel produced from syngas through cobalt catalytic conversion has a very low sulfur and aromatics content and has a high cetane number that makes it very attractive as an alternative

to conventional fuel. Furthermore, it is chemically identical to diesel fuel made from gas or coal. It can be mixed with fossil diesel in conventional engines without changes of infrastructure or existing vehicles. The current market of F-T diesel is important. It is estimated at 697 Mt with a selling price of around 1 296 $ t^{-1} [58]. Furthermore, 49 % of the future syngas market, estimated at 50 000 PJ, will be intended to the synthesis of liquid biofuels mainly F-T diesel [59]. The F-T process producing a mixture of diesel, gasoline and wax is a mature technology and has been proven on a commercial scale for many years by Sasol (F-T diesel from coal) in South Africa.

Methanol is one of the top ten chemicals produced in the world with a global demand of 70 Mt in 2015 [60] and a selling price of 519 $ t^{-1} [61]. About 39 % of the syngas future market will be dedicated to chemicals, mainly methanol. Methanol is a commodity product and a building block for the synthesis of high demand and high-value derivatives (formaldehyde, acetic acid, olefin, dimethyl ether or gasoline). It can also be sold as a liquid fuel or mixed with gasoline. Methanol is produced from syngas using a mature process similar to the petroleum-based process. In addition, the productivity is flexible, for example, dimethyl ether can be synthesized in place of methanol by adding a conversion reactor.

Ammonia has been selected as its market, estimated globally at 137 Mt y^{-1} in 2012 [62], is large and its selling price, of 1052 $ t^{-1} [63], is high. Ammonia synthesis process from syngas is simple and is similar to the petrochemical one. In addition, ammonia is the main consumer of syngas with a percentage of 53 % (3180 PJ y^{-1}) [59]. The syngas dedicated to ammonia synthesis is estimated to reach 3000 PJ in 2040 [59]. The main demand for ammonia is to produce agricultural fertilizer.

Finally, ethanol has an established market and a high demand as a fuel additive (77 Mt) [64]. It can be blended with gasoline to produce a cleaner burning fuel and to reduce the fossil fuel consumption. Mixtures of 10 % or less bioethanol and gasoline can be used in automobiles without modifications to the engines.

4.4.3 Selection of the process configurations

The gasification process selected in the first scenario includes a biomass dryer, a gasifier unit and a syngas cooling system. The gasifier chosen is an air-blown atmospheric circulating fluidized bed reactor from the Foster Wheeler technology since it is proven for biomass gasification; in addition, the produced syngas can be used for electricity production or to fire a lime kiln [65]. The gasifier operates at 1273 K and uses sand as a fluidizing agent. A cyclone is used to separate the sand from the gas exiting the unit and then it is recycled back to the gasifier. A superheated steam dryer from GEA Barr-Rosin technology has been chosen to reduce the biomass moisture content, since up to 90 % of the energy used for drying can be easily recovered from the excess generated steam [66]. Power consumption of the superheater is usually between 150 kWh t^{-1} and 200 kWh t^{-1} evaporated water [66]. It was assumed that steam required for the dryer is produced by the bark boiler while electricity is bought.

For the second case study, an oxygen/steam blows pressurized bubbling fluidized bed developed by the Gas Technology Institute (commercially known as the Renugas process and licensed by Carbona Corporation [57] has been selected as a biomass gasifier. The gasification process considered in this study is mainly used for syngas production from biomass or from a blend of biomass and coal [67]. According to the requirement for a non-diluted syngas with high heating value, the gasification reactor should produce a nitrogen-free gas with high methane

content. Oxygen and steam are used as combustion agent, since air is not suitable for this process [1]. The gasifier is pressurized to eliminate the additional cost of compression for the subsequent catalytic conversion.

The cleaning, conditioning and conversion processes for fuels and chemicals synthesis are adapted from the National Renewable Energy Laboratory (for F-T diesel and ethanol synthesis cases) and the Tennessee Valley Authority (methanol and ammonia).

4.4.4 Costs assessment and economics

The economic performance of the alternatives considered has been estimated by calculating capital investments, operating costs, revenues, and internal rates of return.

Based on the natural gas consumptions in the lime kiln and the bark boiler (Table A.1), syngas and natural gas energy contents (Table A.2), 193 t d^{-1} and 143 t d^{-1} of syngas are required, respectively to fire the lime kiln and to initiate the operation of the bark boiler. Using the assumption that 2 tonnes of biomass give about 1.9 tonne of syngas for an atmospheric FW gasifier [65], an average biomass quantity of about 346 t d^{-1} is used in this case. Moreover, around 30 tonnes of biomass are used daily to produce 41 t d^{-1} of steam for the dryer. Hence, for the first scenario, a total biomass quantity of 377 t d^{-1} is needed, corresponding to 188 dry tonnes of biomass per day (based on 50 % moisture content).

For the second scenario, a design plant size of 1000 t d^{-1} (969 t d^{-1} fed to the gasifier and 31 t d^{-1} used to produce steam for the dryer in the bark boiler) was chosen to satisfy feedstock needs of the first case study and to generate bioproducts. With 350 operating days per year, the annual feedstock requirement is 350 000 t y^{-1}. Cost effects due to plant size were examined as part of the sensitivity analysis. All prices are in US dollars and 2015 is used as a common basis year.

4.4.4.1 **Total capital cost estimation**

The Total Project Investment Costs (TPIC) have been estimated based on data from Swanson et al.[3] using the common pre-engineering estimation method. The values given by this method have an expected accuracy of about -30 % / +50 % but are useful for early screening of potential options [68].

We note that the investment cost related to the production of syngas to fire the lime kiln and to start the operation of the bark boiler is included in the investment costs of the different options. The drying, gasification, and cleaning units are scaled based on the total biomass quantity (used to produce syngas in the lime kiln and in the bark boiler and, to generate bioproducts); however, the syngas conversion units are dimensioned on the base of the feedstock quantity used to generate bioproducts only. The amounts of biomass required for the different scenarios and options are presented in Table 4-1. They are based on the gasifier efficiency and the syngas heating value (Table A.3 in the Appendix).

The TPIC for the different options are presented in Table 4-2. For the first scenario, the required investment is considerably lower than for the scenario 2 since the expected costs are restricted to the replacement of natural gas in the bark boiler and the lime kiln.

In the case of the second scenario, the results show that the production of ammonia requires the highest capital investment cost (212 M$), followed by the synthesis of F-T diesel (184 M$). The products synthesis and storage units are the major cost contributors with respectively 53 M$ and 29 M$ for ammonia and F-T diesel. The reason for the higher investment cost for the ammonia synthesis process is the number of stages required (steam methane reformer, 3 stages water gas shift reactor, pressure swing adsorption unit, methanator, ammonia reactor, etc.). An

important characteristic of the F-T process is the addition of a hydroprocessing area. Therefore, it may be expected that the TPIC would be important. The methanol option has the lowest TPIC (140 M$). The reason is that the syngas for methanol synthesis requires a limited number of conditioning units than the other product options. In fact, once the clean syngas is reformed and water is removed, the ratios of hydrogen, carbon monoxide and carbon dioxide are sufficient for the methanol reaction; no further processing, either additional reforming or shift reactions are needed, before methanol synthesis. Ethanol synthesis cost is about 180 M$. Syngas cleaning and conditioning unit accounts for 22 % of the total equipment installed cost. This is mainly due to the hot cleaning process (catalytic tar cracker) used to satisfy syngas contaminant level requirements for ethanol synthesis.

Table 4-1: Required biomass quantity for the lime kiln, the bark boiler and the production of bioproducts (t d^{-1})

	Biomass for the lime kiln and bark boiler (t d^{-1})	Biomass for bioproducts (t d^{-1})
Scenario 1	346	N/A
Scenario 2		
Methanol	457	513
F-T diesel	260	709
Ethanol	211	759
Ammonia	457	513

Table 4-2: Total project investment costs for scenarios 1 and 2 (M$)

Process Area	Scenario 1	Scenario 2			
		Methanol	F-T diesel	Ethanol	Ammonia
Preprocessing	7.3	9.1	8.8	14	9.1
Gasification	12	28	16	20	28
Syngas Cleaning and conditioning	NA	2.5	11	22	2.7
Product synthesis and storage	NA	14	29	15	53
Power Generation	NA	NA	14	8.9	NA

Air Separation Unit	NA	8.7	8.9	12	8.7
Balance of Plant	NA	14	12	5.4	14
Total Installed Cost	19	76	101	99	116
Indirect Cost	6.1	25	33	32	37
Contingency	5.0	20	27	26	31
Working Capital	4.5	18	24	24	28
Total project investment costs (M$)	34.4	139	184	180	212

4.4.4.2 **Annual operating cost estimation**

The total operating cost consists of variable and fixed costs. The variable operating costs include biomass cost, natural gas credit, waste disposal, catalysts, utilities and other raw materials costs. Is assumed, in this study, that wood chips are the feedstock for the syngas production for the lime kiln, since they are used in the reference dissolving Kraft pulp mill. The estimated cost of wood chip feedstock, including pre-piling, chipping, chips transportation and costs related to forest management, is 40 $ t^{-1} if the wood is collected at a maximum distance of 100 km [28].The fixed operating costs include employee salaries, maintenance fee, general overheads, insurance and taxes [69]. The number of employees used in this study was adapted from the reference case [69] to reflect the feedstock type and capacity. The Canadian salaries estimations for the 2015 year are obtained from Statistics Canada [70].

Table 4-3 presents the variable, fixed and total operating costs for the five options. A total operating cost of about 5 M$ is required for the first scenario to purchase biomass for the lime kiln and for the bark boiler (2.6 M$), to buy electricity for steam dryer (0.9 M$) and to pay employees (fixed cost).

For the second scenario, the higher operating costs are attributed to the production of F-T diesel and ammonia with 18 M$ and 17 M$, respectively while the lower operating costs are for

the methanol synthesis with a total operating cost of about 14 M$. The results depend on the catalysts and chemicals used (for the variable operating costs) and the investments (for the fixed operating costs) as the total biomass quantity and number of employees are the same for all options.

Table 4-3: Operating costs of the considered scenarios (M$)

	Variable operating cost scenarios (M$)	Fixed operating cost scenarios (M$)	Total operating cost scenarios (M$)
Scenario 1	2.93	2.4	5.30
Scenario 2			
Methanol	6.5	7.8	14
F-T diesel	8.4	9.7	18
Ethanol	5.9	9.4	15
Ammonia	6.8	11	17

4.4.4.3 **Estimated annual revenue**

The economic profit of the first scenario turned out to be small as the syngas is used only to substitute natural gas in the lime kiln. This is mainly due to the low price of natural gas and the high feedstock costs. The use of syngas to fire the lime kiln and to start the bark boiler operation is not economically viable at current market conditions. An increase of natural gas price or the biomass gasifier yield, the implementation of carbon emission taxes, or biomass utilization credit could justify, in the future, the use of syngas in the lime kiln.

The expected mill revenue for each option in scenario 2 was obtained by multiplying the total production of the various alternatives by the selling prices. Prices and yields of products considered for the calculation are presented respectively in Table A.2 and Table A.4. Bioproducts selling prices are fixed to the present average market selling prices for fossil options. The sale of

co-products is also considered in this study. The possibility of market price changes in the future was considered in the sensibility analysis.

Results presented in Table 4-4 show that the revenue associated with the ammonia synthesis is important and estimated to 34 M$. This is due to the high ammonia selling price and high process efficiency. Even if the overall efficiency is lower for the F-T process (Table A.4), the high selling price and the significant heating value lead to a higher profit in comparison to methanol and ethanol options (presenting the lowest selling prices).

The internal rate of return (IRR) has been calculated on the basis of the estimation of the capital costs, the operating costs, and the revenue. For a biomass based process, a target rate of return (TRR) of 20 % is assumed to estimate the financial viability of the project [71].

Table 4-4 shows that the rate of return obtained for each option is under the TRR. The methanol selling price should increase by at least 60 % to reach the TRR. F-T diesel and ammonia processes would achieve a TRR of 20 % with 75 % expansion of their respective selling prices. The production of ethanol is not economically viable since it requires a high investment and operating costs and generates a low profit (negative IRR). A minimum selling price (MSP) more than double is required make this option attractive which is not expected.

Table 4-4: Revenues, internal rate of return and minimum product selling price (IRR: Internal Rate of Return, MSP: Minimum Selling Price

	Revenues (M$)	IRR (%)	MSP ($ t^{-1})
Scenario 1	2.53	N/A	N/A
Scenario 2			
Methanol	26	7	992
F-T diesel	31	5	2936
Ammonia	34	6	1842
Ethanol	20	-4	1789

4.4.5 Sensitivity analysis

Two sensitivity analyses were performed to assess the effect of fluctuations in investment cost and biomass price on the required selling prices to reach the TRR. The investment costs shown in Table 4-2 are broadly distributed because the calculation method used has an estimated uncertainty in the range of ± 30 %. The woody biomass price is highly variable and depends on its availability (location) and competitively (between energy sectors). Sensitivity to a large price range has been evaluated to reflect the possible variations and the biomass purchased cost varies by ± 50 %.

The effect of biomass price and capital costs on the required chemicals (methanol and ammonia) and fuels (F-T diesel, ethanol) selling prices to reach the TRR are presented respectively in Fig. 4-2 and Fig. 4-3. Results show that the feedstock cost does not have a large impact on the profitability of the option. In fact, for biochemicals synthesis, Fig. 4-2 shows that at the target rate of return of 20 %, a -50 % change in biomass cost gives a -8 % and -6 % change in the MSP of methanol and ammonia, respectively, which is still high compared to the average fossil selling prices. The same trend is observed for biofuels in Fig. 4-3, showing that at the TRR,

a +50 % change in feedstock price gives a -8 % and -7 % change in IRR for F-T diesel and ethanol selling price, respectively.

However, the investments costs influence significantly the minimum selling prices of the products. Reducing the capital cost by -30 % results in a decrease in the MSP by -33 % for diesel, -26 % for ethanol and ammonia and - 25 % for methanol (Fig. 4-2 and Fig. 4-3). The result is valid when the investment cost is increased by 30 %. Therefore, the capital cost has the potential to significantly influence the economic viability of the projects, thus illustrating the risk associated with the large capital investments in novel technologies.

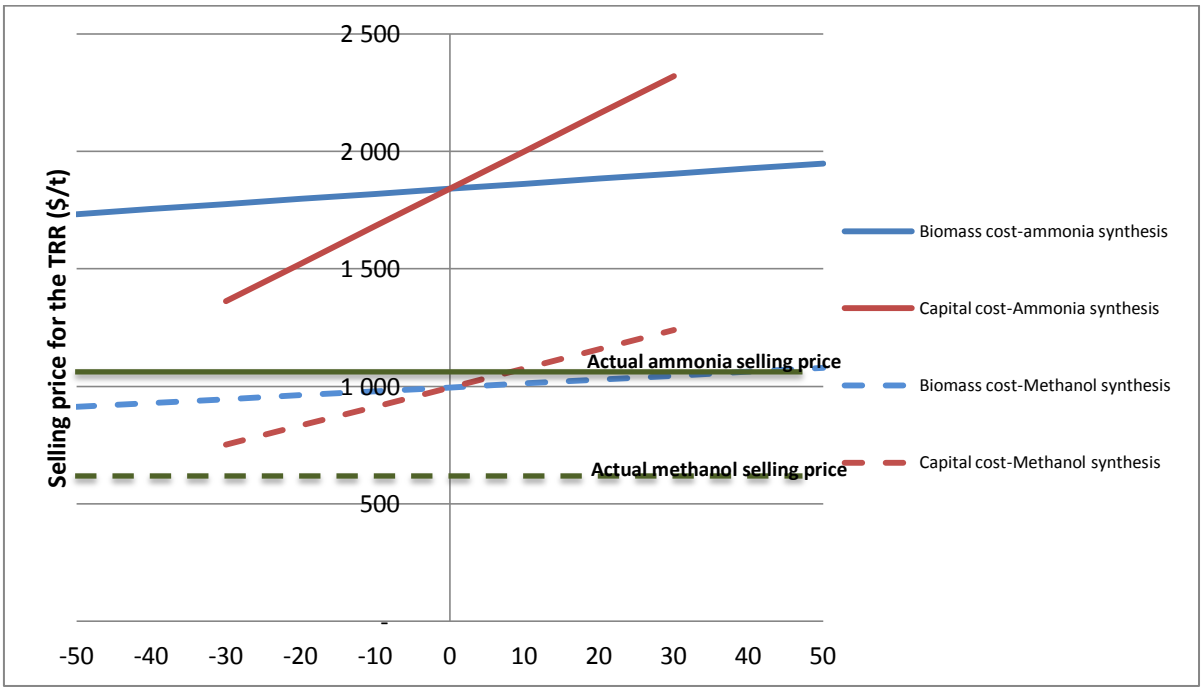

Figure 4-2: Biochemicals selling prices to reach the TRR when the investment cost and biomass price are varied (case of ammonia and methanol)

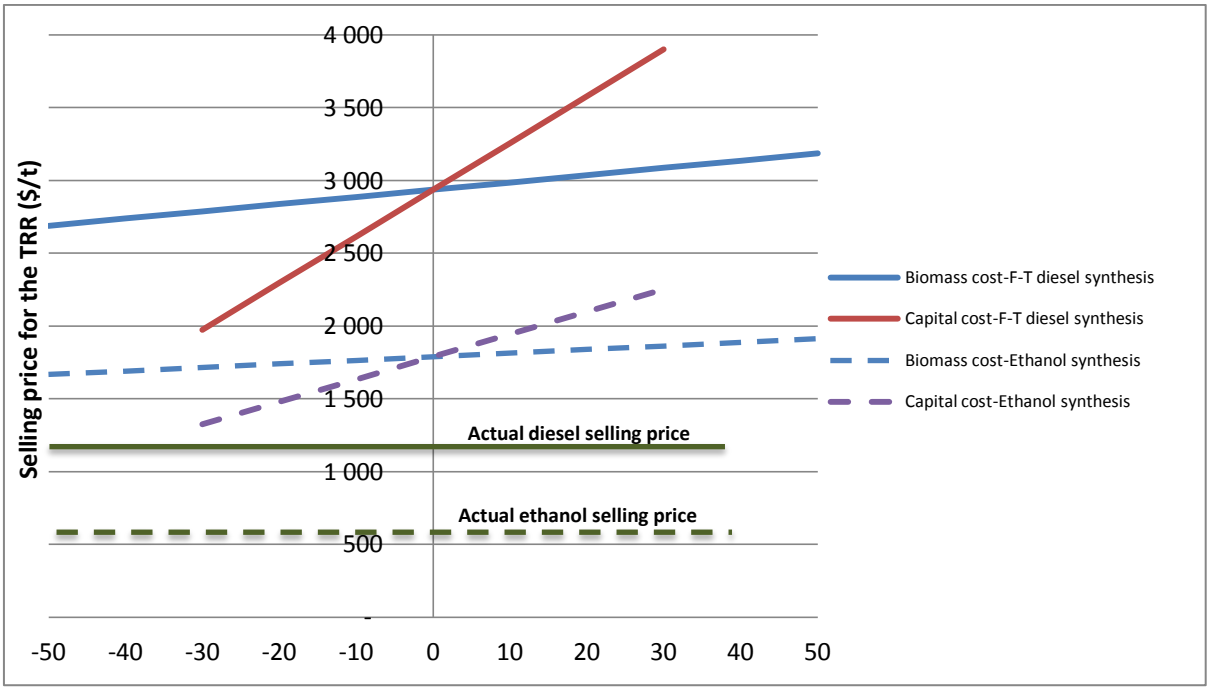

Figure 4-3: Biofuels selling prices to reach the TRR when the investment cost and biomass price are varied (case of F-T diesel and ethanol)

4.5 Conclusion

The main objective of this work was to evaluate the economic viability of the gasification based biorefinery integrated in a pulp and paper mill. The results showed that producing syngas to replace natural gas ensures the environmental sustainability of the GIFBR but is not an economically feasible option. The energy-related investment options considered offer attractive rates of return when products prices are much higher than their fossil substitutes or at low capital investment. A marginal selling price of 60 % is required to reach the TRR for methanol investment option; however, for F-T diesel and ammonia, the rate is fixed at 75 %. The ethanol option relies on a much higher selling price to become attractive to investors. A decrease in capital investments allows methanol and F-T fuel to become competitive with 35 % and 42 % increase in their respective actual selling prices from fossil sources.

4.6 Acknowledgements

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4.7 Appendix A: Supplementary Material

Table A.1: Key parameters of the receptor Kraft mill[72]

Dissolving pulp production (t d^{-1})	820
Wood chips consumption (Gt d^{-1})	1860
Steam production in the recovery boiler (t d^{-1})	2496
Steam production in the bark boiler (t d^{-1})	1248
Steam consumption (t d^{-1})	3696
Bark consumption in the bark boiler (t d^{-1})	461
Natural gas consumption in the bark boiler (t d^{-1})	23.0
Lime production (t d^{-1})	150
Natural gas consumption in the lime kiln (t d^{-1})	31.0
Power production (MW)	13.7

Table A.2: Assumptions for the economic analysis

Plant assumptions		Reference
Plant operation (d y^{-1})	350	Assumption
Project life (y)	20	Assumption
Average scaling exponent	0.70	[73]
Capital installation Factor	2.75	[73]
Fuels kiln heating values		
Natural gas LHV (MJ kg^{-1})	47.1	[74]
Syngas LHV (MJ kg^{-1})	7.50	[65]
Feedstock costs		
Biomass purchased cost ($ GJ^{-1})	2.12	[28]
Natural gas purchased cost ($ GJ^{-1})	2.85	[75]
Products and co-products selling prices		
Electricity ($ kWh^{-1})	0.073	[76]
Methanol ($ t^{-1})	620	[77]
F-T diesel ($ t^{-1})	1296	[58]
Gasoline ($ t^{-1})	1477	[58]
Ethanol ($ t^{-1})	683	[78]
Sulfur ($ t^{-1})	176	[79]
Ammonia ($ t^{-1})	1052	[63]

Table A.3: Fuel high heating values and gasifier mass efficiencies for alternatives

	Fuel Gas Heating Value, HHV, Wet Basis (MJ kg^{-1})	Syngas yield ($t\ odt^{-1}$)	Reference
Fuel kiln	7.5 (LHV)	1.9	[69]
Methanol	9.3	1.4	[80]
F-T diesel	11.4	1.7	[3]
Ethanol	16.1	1.6	[69]
Ammonia	9.3	1.4	[80]

Table A.4: Products yields and co-products generated

Options	Fuel yield ($t\ odt^{-1}$)	By-product	Reference
Methanol	0.498	Electricity	[80]
F-T diesel	0.113	Gasoline, electricity, solid sulfur	[3]
Ethanol	0.215	Mixed alcohols, electricity, solid sulfur	[69]
Ammonia	0.362	Electricity	[80]

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CHAPITRE 5 ARTICLE 2: LIFE CYCLE ASSESSMENT OF ALTERNATIVE OPTIONS FOR GASIFICATION-BASED BIOREFINERY SUPPLY CHAIN

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Highlights:

- From an environmental perspective, dead wood is the most suitable feedstock.
- Grinding of dead wood at the mill side is the preferred biomass supply option.
- Bundling system is not an environmentally friendly comminution option.
- F-T diesel synthesis is the best process option in terms of reduced GHG emissions.
- Methanol performs better than F-T diesel in terms of avoided fossil resources.

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5.1 Abstract

A forest biorefinery configuration based on gasification is an attractive pathway, as the scope of renewable feedstock and bioproducts are wide ranging. The objective of this study is to optimize the supply chain of a gasification-based biorefinery from an environmental perspective. Based on a life cycle analysis approach, methanol and Fischer-Tropsch diesel have been evaluated as potential bioproducts. The work addresses all the stages of the products life cycle: biomass harvesting, residues treatment, feedstock transportation to the gasification-based biorefinery, products synthesis and final transportation to the customers. Forest biomass sources including dead wood, logging and sawmill residues have been considered. Furthermore, several scenarios combining various harvesting and treatment methods, as well as production configurations were examined and compared with respect to greenhouse gases emissions and consumption of fossil resources. The functional unit selected is one dry tonne of biomass fed to the biorefinery. Results have shown that the most attractive supply chain option in terms of reduced climate change impact is dead wood felling, feedstock transportation, and grinding at the mill side with a CO_{2eq} mass of 4.5 kg t^{-1}. This scenario remains as well as the best alternative in terms of reduced fossil resources consumption with a total use of 252 MJ t^{-1}. Results have also shown that F-T diesel synthesis is the best option in terms of reduced greenhouse gases emissions compared to methanol. However, methanol is a better alternative in terms of fossil resources avoided.

Keywords: Biorefinery; Gasification; Forest biomass; Life cycle assessment; Supply chain

5.2 Introduction

Forest biomass is an abundant source of renewable feedstock that can be fractionated and converted into biofuels, biochemicals and other valuable products by thermochemical (gasification, pyrolysis, combustion) and biological pathways (fermentation, anaerobic digestion, etc) [67]. It is now broadly acknowledged that the conversion of forest biomass into bioproducts

in a biorefinery concept could be a mean to reduce fossil fuel consumption and therefore contribute to the stabilization of the greenhouse gases (GHG) emissions in the atmosphere [67].

A biorefinery can be defined as a facility that converts lignocellulosic biomass feedstock into bioproducts. Among the wide range of biorefineries, biomass gasification could be an attractive pathway because of the various syngas valorization options. Four main large-scale biomass gasification pathways exist: syngas can be burned in boilers or lime kilns to produce heat; it can be used in a combined cycle to generate steam and electricity or used as a building block to produce chemical products and transportation fuels [9]. However, to contribute to the stabilization of GHG emissions while being economically attractive, not only the gasification and the syngas conversion technologies should be improved: the challenge is to systematically design and optimize the entire supply chain, from biomass feedstock procurement to bioproducts distribution under economic and environmental criteria. Strategic decisions about feedstock sources, feedstock procurement strategy, products, conversion technologies, size and location of each gasification-based biorefinery should be taken.

The present work is focusing on the optimization of the gasification-based biorefinery supply chain from an environmental perspective. The objective of this study is to evaluate and compare the environmental performance of several gasification-based biorefinery supply chain alternatives: from forest biomass harvesting to bioproducts delivery. Diverse scenarios combining three forest biomass sources (dead wood, logging residues and sawmill residues), two biomass harvesting methods (Cut-To-Length and Full-Tree), various feedstock treatment methods (bundling, grinding, etc.) and two biomass conversion pathways (methanol and F-T diesel synthesis) have been evaluated with respect to climate change and fossil fuel consumption. In addition, the critical steps in each scenario and the alternative with the lowest environmental impact and resources consumption have been identified.

To achieve the objective, a life cycle assessment of the different scenarios has been performed. Each stage of the gasification-based biorefinery supply chain represents a specific set of technical data, forming a logistic system, from the resource in the forest to the final product. The results of this work can be used for strategic decisions to select the most suitable gasification-based biorefinery supply chain scenario.

5.3 Material and methods

5.3.1 Selected forest biomass sources

Three forest biomass sources have been selected. The first category includes logging residues, mainly composed of leftover tops and branches. These residues are generated from harvesting and extracting logs, and are generally considered as non-merchantable wood [23]. They are collected either at the forestside or at the roadside, depending on the harvesting method. Trees damaged by wildlife (animals, insects) or natural disturbances (floods, lightning, fire), mostly referred to dead woods, belong to the second category [23]. Finally, sawmill residues, generated during the timber manufacturing process and particleboard, are also considered in this study.

5.3.2 Definition of the gasification-based biorefinery supply chain

The gasification-based biorefinery supply chain defined in this study includes five main steps: Forest biomass procurement, feedstock treatment, biomass transportation, biomass conversion, and bioproducts distribution, as shown in Fig. 5-1.

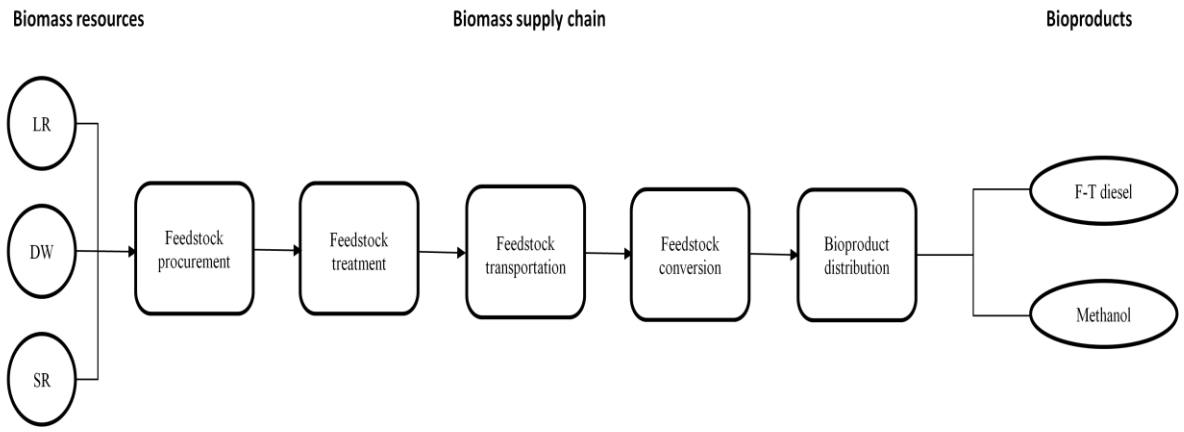

Figure 5-1: Example of a gasification-based biorefinery supply chain

(LR: Logging Residues; DW: Dead Wood; SR: Sawmill Residues; F-T: Fischer Tropsch)

5.3.2.1 Forest biomass procurement system

In the biomass procurement step, wood and dead wood are harvested and collected. Three different forest harvesting methods, which differ in the machines used and the productivities, are

used to harvest the wood; they are Cut-To-Length (CTL), Full-Tree (FT) and Tree-Length (TL) methods [81]. The CTL method consists of felling trees at the forestside above their stumps. Within the same process, they are delimbed, topped and crosscut to the required size. The machine used is mainly a full processor harvester. The transport from the forest to the roadside is generally done with forwarders. As the delimbing is done in the forest, the residues stay on site [81]. With the FT method, the cutting begins with a feller buncher, felling the trees in the forest, while keeping branches and top intact. The transport to the roadside is done either by grapple skidders or cable skidders. The whole trees are processed at the roadside by a delimber, to be further treated or transported directly. Using the TL harvesting method, trees are felled, delimbed and topped at the forestside. Various machines can be used for this configuration, either usual chainsaws or feller bunchers. The felled trees are hauled to the roadside with a cable skidder [81]. In Canada, CTL and FT are the two dominant harvesting methods [82], therefore, these two systems are considered in this work. For dead wood harvesting, it was assumed that damaged trees are cut and loaded respectively with a feller buncher and a grapple skidder system, as no additional machines are needed for this biomass source.

5.3.2.2 **Forest biomass treatment system**

The forest biomass treatment system ensures preprocessing of the feedstock before conversion. The treatment can be performed in the procurement area (forestside, roadside) or on the mill site. The main treatment methods are chipping, grinding and bundling. The main advantage of biomass treatment before transportation is to improve the bulk density of biomass and reach the payload by increasing the mass of feedstock that can be loaded in the same loading volume.

Chipping comminutes the logging residues into wood chips. It produces a high quality product, but requires the raw material to be clean [28]. Grinding is the dominant comminuting technique in an energy wood harvesting system [83]. It is mainly used to comminute branches as well as bundles into hog fuels. It has the highest productivity and can handle even contaminated residues. The disadvantage is that it produces inferior products to chippers in terms of distribution [28]. Only grinders will be considered as a comminuting method in this study as they

are able to comminute degraded biomass (trees damaged by wildlife and fire) and add then flexibility to the feedstock choice.

Bundling systems compact the residues into bales. The bundler could travel throughout the forest and compact the residues at the forestside [81]. Afterwards, the forwarder loads and transports the bundles to the roadside. The bundler can also compact the logging residues at the roadside. In this case, the productivity of this system is higher; however, residues should be forwarded in uncomminuted form with a forwarder. There is a critical decision to be made whether to chip or to bundle the logging residues in the forest or at the roadside. Dead wood can also be grinded before or after handling, depending on the environmental impacts derived from the two scenarios. In this study, the bundling system has not been considered as a treatment alternative because the dead wood bulk density is higher than that of bundles.

Forest biomass can also be transported to the mil in its uncomminuted form. The advantage here is to reduce the environmental impacts and the costs related to the various treatment systems. In this case, the mill should have an in-plant grinder which has the advantage to improve the environmental performance related to biomass treatment, as the productivity of the stationary grinder is higher than that of the mobile one [84]. Consequently, there is again a critical decision to be made whether to treat biomass before or after transportation.

5.3.2.3 **Biomass conversion**

The biomass gasification and syngas conversion processes ensures the synthesis of a variety of biofuels and biochemicals. The gasification process consists of three successive steps: biomass preparation (drying and grinding), gasification, i.e. the production of syngas and finally, syngas cleaning and conditioning [9]. Two options of syngas catalytic conversion have been selected for this study; F-T diesel and methanol synthesis. The F-T diesel is considered as a transportation fuel, while methanol is assumed to be sold as a chemical product. The F-T diesel synthesis has been preselected, as it is chemically identical to the diesel produced from gas or coal and it can be mixed with conventional fuels [85]. In addition, the F-T synthesis is a proven technology in operation at commercial scale for many years by the Sasol company [3]. Methanol is produced from syngas using simple and mature processes, similar to the petroleum-based process. It is a commodity chemical and a building block for the synthesis of derivatives such as formaldehyde,

acetic acid, olefin, dimethyl ether or gasoline. Methanol is one of the top ten chemicals produced globally [67].

The process configurations considered for the biomass to F-T diesel and methanol synthesis are presented respectively in Fig. S.1 and Fig. S.2 in the Appendix. These figures are adapted from previous works conducted by the National Renewable Energy Laboratory (for F-T diesel) and the US Department of Energy (for methanol).

5.3.2.4 **Biomass and bioproducts transportation**

When trees are processed, logging residues are available at the forestside or at the roadside, depending on the harvesting method. They can be transported to the mill in uncomminuted form, as hogs or bundles. Dead wood can be handled in its uncomminuted form or as hog fuel. The biomass and the bioproducts transportation system include the infrastructure required to transport, load and unload the feedstocks (from the procurement area to the biorefinery) and the bioproducts (from the biorefinery to the customer). Truck has been selected as a transportation mode. It has been chosen for biomass transportation as logging residues and dead wood are usually scattered on the procurement sites and distributed over large areas.

5.3.3 **Goal& scope definition**

In this study, Life Cycle Analysis (LCA) has been used to investigate and compare the environmental performance (climate change and fossil resources consumption) of the gasification biorefinery supply chain scenarios in a Canadian context. The functional unit chosen is one dry tonne of biomass. All the energy and mass flows in the inventory phase have been normalized to this unit.

5.3.4 **Scenarios and system boundaries definition**

The gasification based-biorefinery supply chain scenarios compared in this study are:

1. Biomass sources: logging residues, dead wood and sawmill residues;
2. Wood harvesting systems: Cut to Length and Full Tree;

3. Logging residues treatment systems: bundling (at the forestside and at the roadside) and grinding (roadside);

4. Logging residues and dead wood transportation forms: Uncomminuted from, bundles and hogs;

5. Forest biomass conversion processes: F-T diesel synthesis and methanol synthesis;

The combination of the alternatives is illustrated in Fig. 5-2, showing ten different scenarios.

To ensure that the compared systems are functionally equivalent, the impacts associated with the avoided products or processes should be subtracted. In this study, the avoided products are methanol and diesel from fossil resources. Boundaries expansion approach has been used to include them. It is a consequential approach as the impacts of the consequences associated with the implementation of the biomass conversion processes are examined. In fact, if a renewable product is used, it can avoid the production of the fossil one. Therefore, the benefit of the bioproduct is shown by subtracting from the life cycle inventory the impacts associated with the amount of the fossil product.

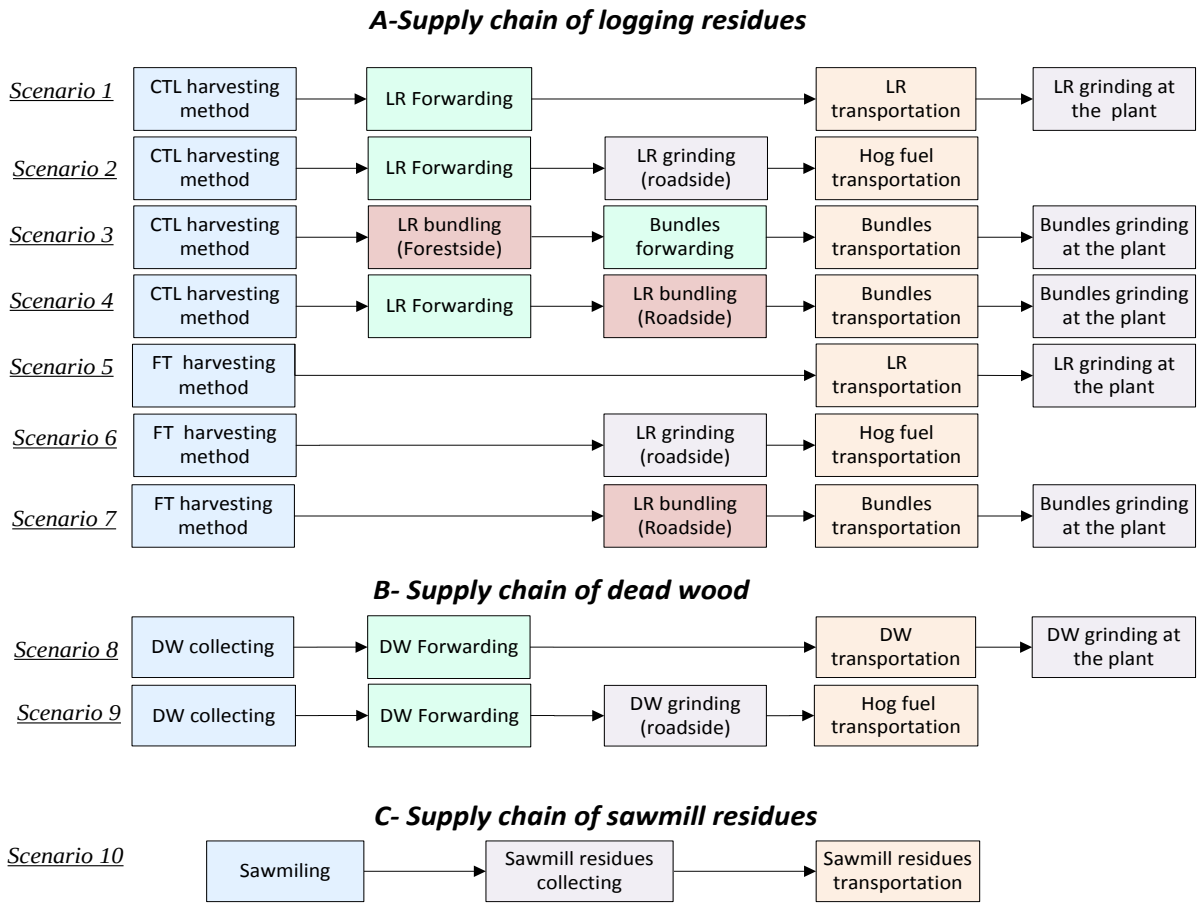

Figure 5-2: Scenarios of the gasification based-biorefinery supply chains

(CTL: Cut-to-length; FT: Full-Tree; LR: Logging Residues; DW: Dead Wood)

5.3.5 Allocation procedure

Wood harvesting operations and sawmilling generate logging and sawmill residues as by-products respectively. Furthermore, syngas conversion processes produce co-products (in the case of F-T diesel, the co-products are electricity, gasoline and sulfur cake; in the case of methanol, only electricity is considered as a co-product). Allocation based on mass balance has been used for the by-products (logging residues and sawmill residues) which means that the environmental burdens are distributed according to the mass percent of each product. The environmental impacts of the wood harvesting methods allocated to the logging residues are based on the average percentage of logging residues recovery using CTL and FT harvesting

methods (respectively 48 % and 61 % of the total yield of the stand) [81]. For sawmilling operations, the sawmill residues represent 49 % of the total products, while the lumber represents 51 % [86].

For the syngas conversion processes, no allocation between the products has been considered, since the environmental performance of the overall gasification-based biorefinery has been evaluated. In this case, co-products are considered as avoided products (as they already have existing markets).

5.3.6 Data acquisition

Data from the literature and from the life cycle inventory databases are collected for each process considered in the supply chain scenarios. Inventories include productivities of the machines, energy and material consumptions (in terms of diesel, electricity, heat, chemical products) as well as machines emissions. All the energy and mass flows over the life cycle of each process are normalized to the defined functional unit. A description of the processes and database used is given in the Appendix (Table A.1).

For the forest biomass procurement step, inventory data are collected from the work of Kenney [87] and are available in Table A.2 in the Appendix. Data regarding the wood and dead wood treatment systems are presented in Table A.3 in the Appendix. Fuel consumptions and productivities of the bundling systems (roadside and forestside) are extracted from Karha and Vartiamaki [88]. For mobile grinding, data from Yoshioka et al. [89] have been used. The logging residues and the dead wood mobile grinders have different consumptions due to the different inputs.

For grinding bundles and forest residues (dead wood, logging residues) at the mill side, in-plant stationary electric grinder has been considered. The power required for the electric chippers is 1.1 MW [3]. As logging residues, dead wood and bundles have different densities, the related electricity consumption changes, it is estimated to 5.5 kWh t^{-1} for logging residues, 0.5 kWh t^{-1} for dead wood and 2.2 kWh t^{-1} for bundles. The emissions related to the treatment machines are obtained from the Ecoinvent database (Table A.1).

The sawmill residues procurement inventory was developed using mass and energy balances. The primary products of sawmills are lumber, whereas sawmill residues (in form of barks, chips and sawdust) contribute to about 49% of the output [86]. Operations to produce timber consume energy in the form of electricity (0.07 GJ t^{-1}) and heat (0.78 GJ t^{-1}) based on the work of Li et al. [86] .

The energy and material flows involved in the F-T diesel and methanol synthesis processes are based on simulations developed by the National Renewable Energy Laboratory [3] and the Department of Energy [90] respectively using the software Aspen Plus. The capacity of the gasification unit is 2000 t d^{-1} of biomass. The inputs and outputs data for the conversion processes are normalized for one dry tonne of feedstock and are summarized respectively in Table 5-1 and Table 5-2.

Table 5-1: Input data of the F-T diesel and methanol synthesis processes (based on 1 dry tonne of biomass)

	F-T diesel	**Methanol**
Feedstock preparation		
Air (m^3)	-	265
Natural gas (m^3)	-	49.1
Gasification		
Air (m^3)	532	486
Heat (MJ)	153	-
Syngas cleaning		
Quench water (m^3)	325	50.9
Air (m^3)	0.139	-
Syngas conditioning		
Heat (MJ)	426	2535
Air (m^3)	-	1517
Natural gas (m^3)	-	330
Power generation		
Air (m^3)	675	-

Table 5-2: Output data of the F-T diesel and methanol synthesis processes based on 1 dry tonne of biomass (a: output sent to waste treatment, b: output released to the atmosphere, c: output sold as product or by-product)

	F-T diesel	**Methanol**
Feedstock preparation		
Waste water [a] (kg)	222	-
Flue gas [b] (kg)	-	1910
Gasification		
Flue gas [b] (kg)	735	-
Dry ash [b] (kg)	59.0	27.0
Syngas cleaning		
Flue gas [b] (kg)	5.75	1.10
Carbone dioxide [b] (kg)	589	-
Sulfur cake [c] (kg)	0.350	-
Waste water [a] (kg)	694	470
Wet ash and char [b] (kg)	0.910	-
Gas contaminants [b] (kg) (mix of ammonia and hydrogen sulfide)	-	0.580
Syngas conditioning		
Gas contaminants [b] (kg)	0.700	-
Carbone dioxide [b] (kg)	-	726
Flue gas [b] (kg)	-	3136
Product and bioproducts synthesis		
Diesel [c] (kg)	103	-
Gasoline [c] (kg)	43.5	-
Methanol [c] (kg)	-	499
Power generation		
Electricity [c] (KWh)	377	301
Flue gas [b] (kg)	977	-

The fuel and lubricant consumptions for biomass and bioproducts transportation, loading and unloading are shown in Table 5-3. Values obtained for biomass transportation are based on the bulk densities of the different feedstock forms (Table A.5) and data from Table A.4. For products transportation, the electricity required for products loading and unloading (pumping) has been included. The emissions released during truck operation (fuel burned) have also been considered based on process from Ecoinvent database.

Table 5-3: Fuel and lubricant consumptions for biomass and bioproducts transportation, loading and unloading

	Total fuel consumption (L t^{-1})	**Total lubricant consumption (L t^{-1})**
Feedstock		
Logging residues	18.6	0.37
Logging residues, hog fuel form	4.27	0.09
Logging residues, bundle form	7.96	0.16
Dead wood	1.92	0.04
Dead wood, hog fuel form	1.20	0.02
Sawmill residues	2.44	0.05
Bioproducts		
Methanol	2.06×10^{-2}	4.12×10^{-4}
F-T diesel	6.25×10^{-3}	1.25×10^{-4}

5.4 Results and discussion

The alternatives related to the supply chain steps and the selected scenarios have been evaluated using the life cycle impact assessment method IMPACT 2002+ [49] and compared with regard to fossil fuel consumption and climate change performance (GHG accountings). Climate change has been chosen as it is a very relevant metric given the current context. Nonetheless, research shows that it is an incomplete representative of the environmental performance of products because it ignores several other types of impacts (environmental impacts related to emissions of toxic substances, etc.) [91]. Fossil fuel consumption has then be added

since it serves as a screening indicator for several environmental impacts such as global warming, resource depletion, acidification, tropospheric ozone formation, etc. [92].

5.4.1 Environmental characterization of the life cycle steps

To better evaluate the environmental impacts of each stage, the supply chain was divided into four steps described below.

5.4.1.1 Wood/Dead Wood harvesting

Table 5-4 presents the LCA results for the feedstock harvesting and treatment methods based on a dry tonne of feedstock. Results show that the CTL harvesting method (considering only the harvester) emits less GHG and consumes less fossil resources than the F-T system. The difference can be explained by the number of machines used. In fact, even though the feller buncher and the grapple skidder used in the F-T method are more productive, the F-T system uses 3 machines, the time they need to process one dry tonne of wood is then longer, and therefore the fuel consumption and the related emissions are higher. For dead wood, the environmental impact of the harvesting system is clearly higher than that of the two wood harvesting systems. The reason is that the system used (composed of a feller buncher and a grapple skidder) [87] is less productive due to the low density of dead wood compared to tree sections (Table A.5).

Table 5-4: Environmental profile of feedstock harvesting and treatment methods

	CO_{2eq} emissions (kg t^{-1})	**Fossil resources demand (MJ t^{-1})**
Wood and dead wood harvesting methods		
CTL harvesting system	0.07	8.29
FT harvesting system	0.11	12.7
Dead wood system	1.04	122
Feedstock treatment methods		
Logging residues treatment options		
Bundling (forestside)	30.4	883
Bundling (roadside)	25.4	736
Grinding (roadside)	16.3	335
Grinding (mill side)	0.09	4.33
Bundles grinding (mill side)	0.04	1.85
Dead wood treatment options		
Grinding (roadside)	4.35	89.4
Grinding (mill side)	0.01	0.44
Sawmill residues procurement	52.1	828

5.4.1.2 **Feedstock treatment**

For logging residues and dead wood resources, grinding at the mill side is the best treatment option in terms of fossil resources consumption and GHG emissions. This result is predictable, as the electricity produced in Quebec used in the plant has a very low carbon footprint compared to fossil fuels used for forestside and roadside grinding. Furthermore, large scale in-plant grinders have a higher productivity than mobile machines. The less attractive comminuting technique for logging residues is bundling. This is due to the low bundler productivity especially at the forestside (due to the low concentration of the logging residues in the cutting areas) and then the high fuel consumption to get bundles. This is also the results of the high demand of primary energy needed to produce packaging films for bundles. In terms of GHG emissions, sawmill

residues procurement process presents the worst climate change performance. This is due to the huge amount of GHG emitted by the sawmilling activities and to the allocation method used. On the other hand, sawmill residues procurement consumes more fossil resources than roadside treatment systems and less than bundling at the forestside. This is again due to the high fossil resources required for sawmilling.

5.4.1.3 **Biomass conversion processes**

Fig. 5-3 shows that the F-T process contributes less to climate change compared to methanol production. It remains the best option even considering the avoided fossil diesel and co-products use. On the other hand, methanol process shows a lower performance regarding climate change indicator (CO_{2eq} mass of 428 kg t^{-1} for the methanol synthesis process and 83.9 kg t^{-1} using boundaries expansion). In fact, as it is observed in Fig. 5-3, this process emits a considerable quantity of CO2eq, during the syngas conditioning and the methanol synthesis stages (395 kg t-1 compared to 107 kg t-1 for the F-T diesel synthesis process) due to the quantity of contaminants and gas emitted. Regarding fossil fuel consumption indicator, as shown in Fig. 5-4, F-T process is found also to be the best option with an estimated resources consumption of about 2248 MJ t^{-1} of forest biomass compared to 5270 MJ t^{-1} for the methanol synthesis process. In fact, the main energy source for the methanol synthesis process is natural gas and for the F-T diesel production are steam from combined cycle system and heat from char combustion. However, methanol becomes the best alternative when considering by-product (power generation) and fossil methanol avoided (-18600 MJ t^{-1} compared to -6370 MJ t^{-1} for F-T diesel synthesis process). The main cause could be the high consumption of primary energy needed to produce fossil methanol which is avoided in this case (Fig. 5-4).

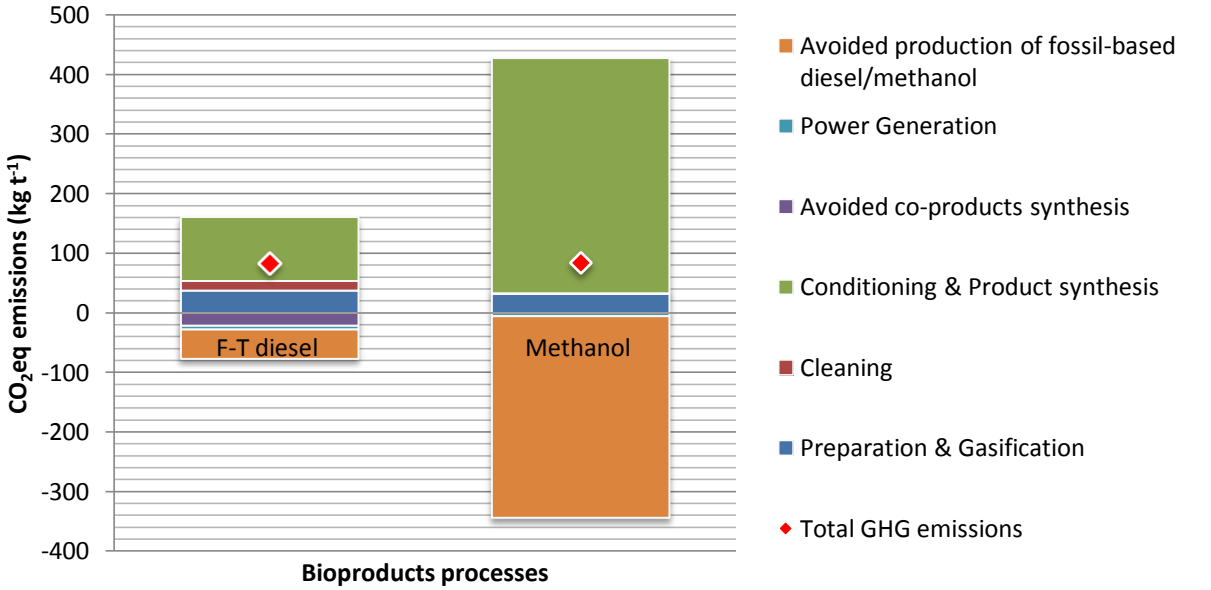

Figure 5-3: Greenhouse gas emissions per tonne of biomass used for the evaluated bioproduct systems

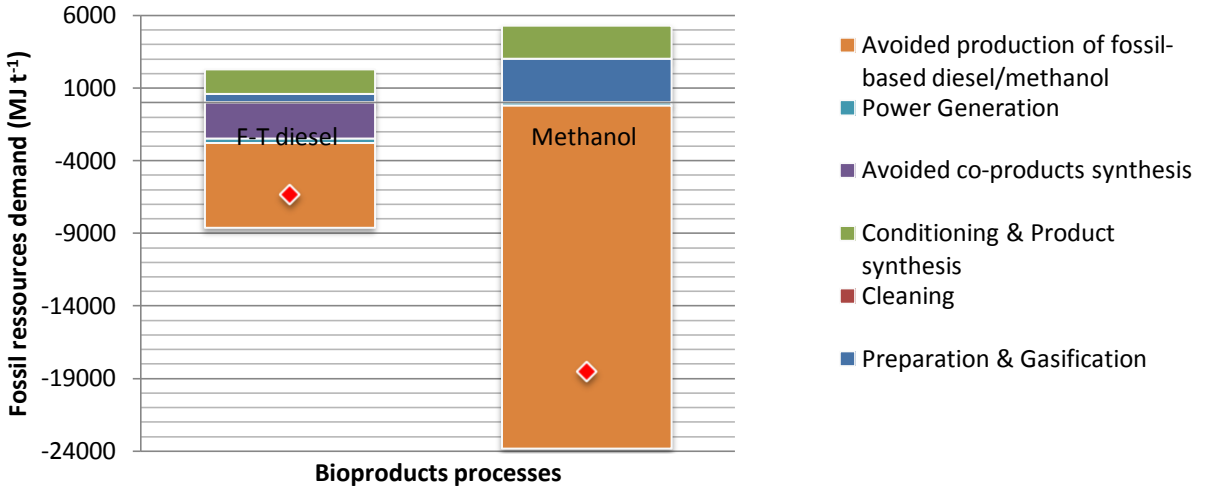

Figure 5-4: Fossil resources demand per tonne of biomass used for the evaluated bioproduct systems

5.4.1.4 **Biomass and products transportation**

As shown in Table 5-5, the environmental performances of logging residues transportation (in terms of climate change and fossil resources consumption) are clearly lower than those of dead wood and sawmill residues. The result is directly linked to the bulk density and the moisture content of the feedstock type and form (Table 5-5). The environmental performances increase as the bulk density raises and the moisture content decreases.

Bioproducts transportation have better environmental performance than biomass transportation because methanol and F-T diesel have higher densities compared to biomass (Table A.5). Furthermore, the F-T diesel transportation emits less GHG and consumes less resources than methanol transportation as the yield of F-T diesel (per one dry tonne of biomass) is lower than that of methanol. The transportation of F-T diesel requires only 0.31 MJ t^{-1} of primary energy input and emits a CO_{2eq} mass of about 0.03 kg t^{-1}, while methanol transportation consumes 1.02 MJ t^{-1} of fossil resources and emits a CO_{2eq} mass of about 0.11 kg t^{-1}.

5.4.2 **Comparison of the scenarios**

Ten scenarios combining different forest biomass resources and defined supply chain alternatives are compared with respect to GHG emissions and fossil resources consumption.

As can be observed in Fig. 5-5, scenario 8 is the most attractive supply chain option in terms of GHG emissions. This configuration considers dead wood felling, feedstock transportation, and grinding at the mill side with a total CO_{2eq} mass of 4.5 kg t^{-1}. The worst performance is attributed to scenario 10 which consist of using sawmill residues as potential feedstock with a total CO_{2eq} mass of 54 kg t^{-1}.

Fig.5-6 shows that the highest fossil resources consumption is attributed to scenario 3 since a large quantity of non-renewable resources is consumed during the bundling step (883 MJ t^{-1} of logging residues). Scenario 8 remains the best alternative in terms of fossil fuel consumption with a total use of 252 MJ t^{-1}. We can conclude that dead wood is the best feedstock option compared to logging and sawmills residues. In the context of this study, it is preferable to transport dead wood in its uncomminuted form than in hog fuel form since environmental benefits of biomass treatment could not improve the performance of the transportation step.

Considering only logging residues valorization options, Fig. 5-5 and Fig. 5-6 show that supply chain scenarios considering CTL felling system (scenario 1 to 4) have lower environmental performance than those examining FT system (scenario 5 to 7) even though, separately the CTL is, environmentally a more interesting option than the FT one. This is due to the high quantity of GHG emitted and fossil fuel consumed by the forwarders used in those configurations as the delimbing is done in the forest and the logging residues remain on site.

It is interesting to note that treating the logging residues before transportation using grinding system (scenarios 2 and 6) does not improve the environmental performance of the supply chain in terms of GHG emissions however; it is an interesting option regarding fossil fuel consumption.

Table 5-5: Environmental profile of feedstock and bioproducts transportation

	CO_{2eq} emission ($kg\ t^{-1}$)	**Fossil resources demand ($MJ\ t^{-1}$)**
Feedstock		
Logging residues-uncomminuted form	9.90	922
Logging residues-hog fuel form	2.31	212
Logging residues-bundle form	4.32	395
Dead wood-uncomminuted form	1.31	95.1
Dead wood-hog fuel form	1.00	59.4
Sawmill residues-mixed bark and sawdust	1.53	121
Bioproducts		
Methanol	0.11	1.02
F-T diesel	0.03	0.31

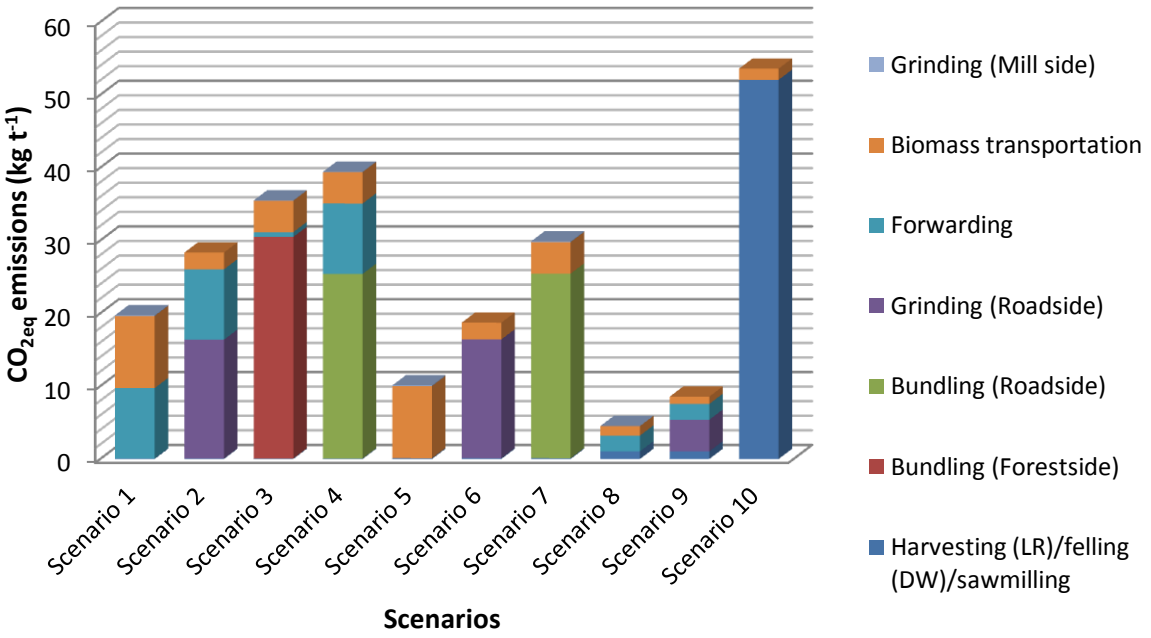

Figure 5-5: Contribution of the supply chain steps to climate change (bioproducts synthesis excluded)

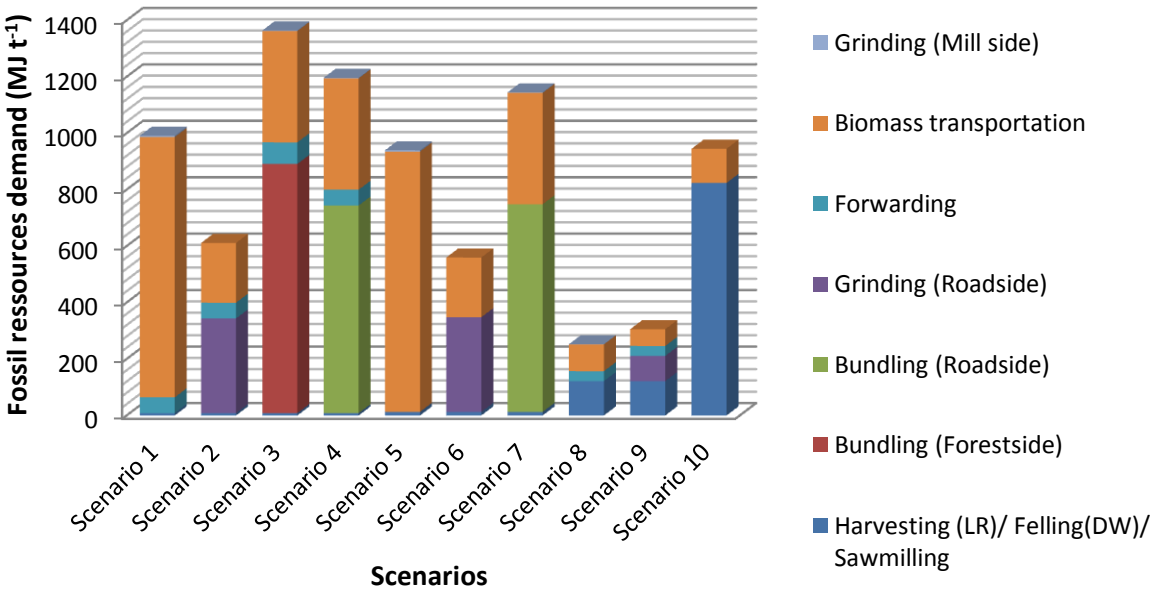

Figure 5-6: Contribution of the supply chain steps to fossil fuel consumption (bioproducts synthesis excluded)

5.4.3 Sensitivity analysis

Three parameters were chosen for the sensitivity analysis: allocation method for sawmill residues production, biomass truck capacity and feedstock transport distance. Sawmill residues can be allocated in accordance with their economic value as they already have an existing market. Sawmill residues and lumber costs have been taken respectively from the average Canadian price in 2011, 17 \$ m^{-3} [93] and from the Quebec lumber prices in 2015, 190 \$ m^{-3} [94]. The truck capacity variable has been selected for sensitivity analysis as it has an impact on the transportation stage emissions. In fact, using a large size truck of 40 tonnes could decrease the number of trips required to handle the same biomass quantity. Finally, the transport distance between the feedstock procurement sites and the gasification-based biorefinery has been increased from 150 km to 300 km to evaluate the impact of the biomass transportation over exceedingly long distance. The results of the sensitivity analysis are presented in terms of variation of the total GHG emissions (Fig. 5-7) and fossil resources consumption (Fig. 5-8) for each scenario, compared to the results of the basic case study. By changing the allocation method for sawmill residues in scenario 10, the CO_{2eq} emissions and the fossil resources consumptions drop from 54 kg t^{-1} to 10 kg t^{-1} and from 945 MJ t^{-1} to 259 MJ t^{-1} respectively (scenario 10 in Fig. 5-7 and Fig. 5-8, respectively). In fact, sawmill residues decrease from 44 % to 8 % of the total products, while lumber represents 92 %. Therefore, heat, electricity and fuel consumptions, which are responsible of the environmental impact, decrease considerably. As shown in Fig. 5-7 and Fig. 5-8, scenario 8 remains the best alternative in terms of climate change and fossil resources consumption.

Results (sensibility analysis b and c) show also that changing respectively the biomass truck capacity and the transport distance does not affect the scenarios trend (only the contribution of the transportation step has been changed). However, increasing the biomass truck capacity (sensitivity analysis b) has a lower impact then increasing the transportation distance (sensitivity analysis c) for all the scenarios and for the considered environmental indicators.

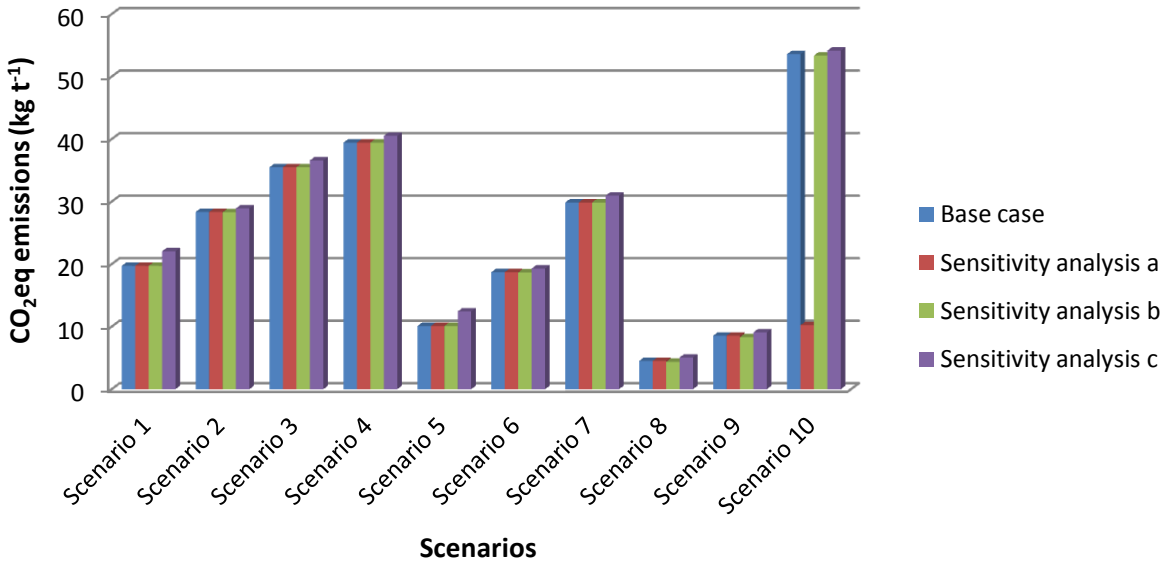

Figure 5-7: Impact of (a) sawmill residues allocation method, (b) biomass truck capacity and (c) transport distance on climate change

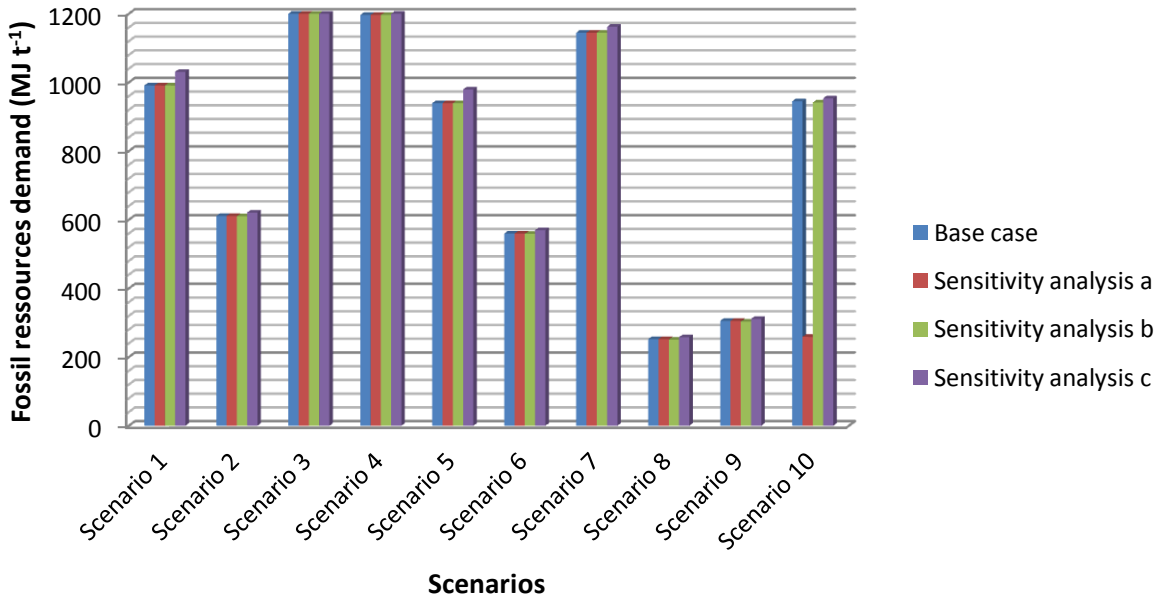

Figure 5-8: Impact of (a) sawmill residues allocation method, (b) biomass truck capacity and (c) transport distance on fossil resources demand

5.5 Conclusions

In this article, an LCA study was conducted to assess the environmental performance of various gasification-based biorefinery supply chain alternatives: from biomass resources selection to bioproduct delivering. Ten scenarios combining three forest biomass sources (dead wood, logging residues and sawmill residues), two biomass harvesting systems (Cut-To-Length and Full-Tree), different feedstock treatment methods (bundling, grinding, etc.) and two biomass conversion pathways (methanol synthesis and F-T diesel synthesis) have been evaluated in terms of climate change and fossil resources consumption. The environmental assessment identified dead wood as the most attractive forest feedstock regarding the selected impact categories, followed by logging residues. For those two biomass resources, results show that, in terms of climate change, grinding at the mill side is more attractive than grinding at the roadside, even though transportation of hog fuel has lower environmental impact compared to unprocessed biomass. Regarding fossil fuel consumption, the same conclusion remains valid for dead wood, however, for logging residues, roadside grinding becomes the most attractive treatment alternative since handling uncomminuted residues consumes a considerable quantity of fossil diesel. Concerning bioproducts, F-T diesel synthesis process was found to be the most promising alternative in terms of climate change and fossil fuel consumption. Nevertheless, when considering boundaries expansion, F-T process remains the best option in terms of climate change but methanol process becomes more interesting regarding fossil fuel consumption. However, to make the best decision about the supply chain configuration, carbon stock change in forests and soil needs to be included in the strategic assessments of the GHG emissions. The choice of a forest bioenergy feedstock to substitute fossil energy sources affects the evolution of carbon sequestration in ecosystems. For instance, deadwood would release carbon to the atmosphere if left in the forest instead of being used in a biorefinery to produce F-T diesel or methanol. Moreover, there is a carbon payback time required before obtaining benefits in terms of avoided GHG emissions [95]. The carbon payback time to compensate this so-called "carbon debt" depends on the biomass resource used to generate bioenergy. A long carbon payback time means an increase of the global warming impact on the short-term. For this work, a short carbon payback time can then be expected since the forest biomass considered are whether left in the ground to decay in the forest, burned as part of the forest management (logging residues and dead

wood) or sold as a by-product from wood processing (sawmill residues). Carbon debt depends also on the effectiveness with which biomass feedstock displace fossil energy sources. However, the calculation of the carbon payback time is out of the scope of this study.

The gasification-based biorefinery supply chain scenarios differ in terms of environmental performances and costs. Future work needs to be undertaken to design and optimize the entire supply chain under economic and environmental criteria that can ensure the stabilization of the GHG emissions, while being economically attractive. The multicriteria optimized supply chain enables making strategic decision when selecting the biomass gasification pathway.

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5.8 Appendix

Key assumptions for life cycle analysis

Table A.1: Description of the processes and databases used

Process	**Process/database used**
Biomass treatment and transportation	
Sawlogs production	Sawlog and veneer log, softwood, measured as solid wood under bark (CA-QC) | softwood forestry, mixed species, boreal forest | Alloc. Def, U. (Ecoinvent 3)
Heat production	Heat, district or industrial, other than natural gas (GLO)| heat production, wood chips from post-consumer wood, at furnace 300kW | Alloc. Def, U. (Ecoinvent 3)
Mobile chipper	Process extracted from: Wood chipping, chipper, mobile, diesel, at forest road (RoW)| wood chipping, mobile chipper, at forest road | Alloc. Def, U.

emissions	(Ecoinvent 3)
Stationary chipper emissions	Process extracted from: Wood chipping, industrial residual wood, stationary electric chipper (RoW)| processing | Alloc Def, U. (Ecoinvent 3)
Forwarder emissions	Process extracted from: Forwarding, forwarder (RoW)| forwarding, forwarder | Alloc Def, U. (Ecoinvent 3)
Bundler emissions	Process extracted from: Harvesting/bundling, energy wood harvester (RoW)| harvesting/bundling, energy wood harvester | Alloc Def, U. (Ecoinvent 3)
Lubricating oil production	Lubricating oil (GLO)| market for | Alloc Def, U. (Ecoinvent 3)
Truck emissions	Process created from: Transport, truck >20t, EURO1, 100 % LF, empty return/GLO Mass. (Agri-footprint-mass allocation)
Bioproducts synthesis	
Steam production	Steam, in chemical industry (GLO)| market for | Alloc Def, U. (Ecoinvent 3)
Electricity production	Electricity, high voltage (CA-QC) | market for | Alloc Def, U. (Ecoinvent 3)
Natural gas production	Natural gas, high pressure (CA-QC) | market for | Alloc Def, U. (Ecoinvent 3)
Naphtha production	Naphtha (RoW)| market for | Alloc Def, U. (Ecoinvent 3)
Diesel production	Diesel (RoW)| market for | Alloc Def, U. (Ecoinvent 3)
Methanol production	Methanol (GLO)| market for | Alloc Def, U. (Ecoinvent 3)

Table A.2: Inventory data for wood and dead wood harvesting machines [87]

Machine	**Fuel use** (L PMH^{-1})	**Lubricant use** [8] (L PMH^{-1})	**Productivity** [9] (t PMH^{-1})
Wood extraction			
Cut-to-Length method			
Harvester	19.1	0.38	11.6
Forwarder	11.1	0.22	16.0
Full-Tree method			
Feller-buncher	26.2	0.52	48.7
Grapple Skidder	23.6	0.47	26.0
Delimber	17.3	0.35	32.3
Dead wood extraction			
Feller-buncher	26.2	0.52	25.2
Grapple Skidder	23.6	0.47	13.5

[8] Lubricant use ratio: 0.02 liter per liter of fuel consumed based on the work of Kärhä and Vartiamäki [96]O'Connor D, (S&T)^2 Consultants Inc. Biodiesel GHG emissions, past, present, and future BC, Canada; 2011. Contract No.: T39-T1a.

[9] The productivity is in green tonne per Productive Machine Hour (PMH)

Table A.3: Inventory data for logging residues and dead wood treatment machines

Machine	**Fuel use** (L PMH^{-1})	**Productivity** (t PMH^{-1})	**Reference**
Logging residues bundler (Forestside)	18.0	2.1	[88]
Logging residues bundler (Roadside)		2.5[10]	
Logging residues grinder (Roadside)	71	21	[89]
Dead wood grinder (Roadside)		45[11]	
Logging residues forwarder	11.1	1.2	[87, 88]
Bundle forwarder		4.5	[87, 88]

[10] The productivity is assumed to be 20% higher due to the accessibility of biomass at roadside

[11] The dead wood grinder productivity is adapted from [12] S3D ingénierie. Technologies de gazeification 2014 [02-02-2016]. Available from: http://www.gazeification.info/technologies-de-gazeification.

Table A.4: Key inventory data for feedstock and products transportation

Parameters (Units)	**Assumed value**	**Sources**
Average truck fuel use (L tkm^{-1})	0.015	[97]
Distance (km)	150	[98]
Biomass transportation		
Volume capacity of biomass truck (m^3)	70.0	[84]
Payload of biomass truck (t)	22.7	[84]
Biomass loader fuel use (L/PMH)	26.3	[87]
Biomass loader capacity (m^3/PMH)	73.9	[87]
Bioproducts transportation		
Volume capacity of product truck (m^3)	63.5	[99]
Payload of bioproducts truck (t)	59	[99]
Truck filling grade (%)	95.0	[99]
Loader energy use (MJ t^{-1})	9.15×10^{-3}	[100]
Methanol density (kg m^{-3})	791	[101]
Diesel density (kg m^{-3})	850	[102]
Methanol yield[12] (kg t^{-1})	460	[90]
F-T diesel yield (kg t^{-1})	150	[3]

[12] The methanol and F-T diesel yields are per green tonne of biomass

Table A.5: Bulk densities of different types of biomass

Feedstock form	**Moisture content (%, wet basis)**	**Bulk density (kg m^{-3})**	**Sources**
Tree sections	12	865	[84]
Logging residues	50	80.0	[84]
Hog fuel (from logging residues)	50	350	[83]
Bundle	45	170	[84]
Dead wood	12	448	[25]
Hog fuel (from dead wood)	12	746	[25, 103]
Sawmill residues[13]	42	541	[103]

Process flow diagrams of methanol and F-T diesel synthesis

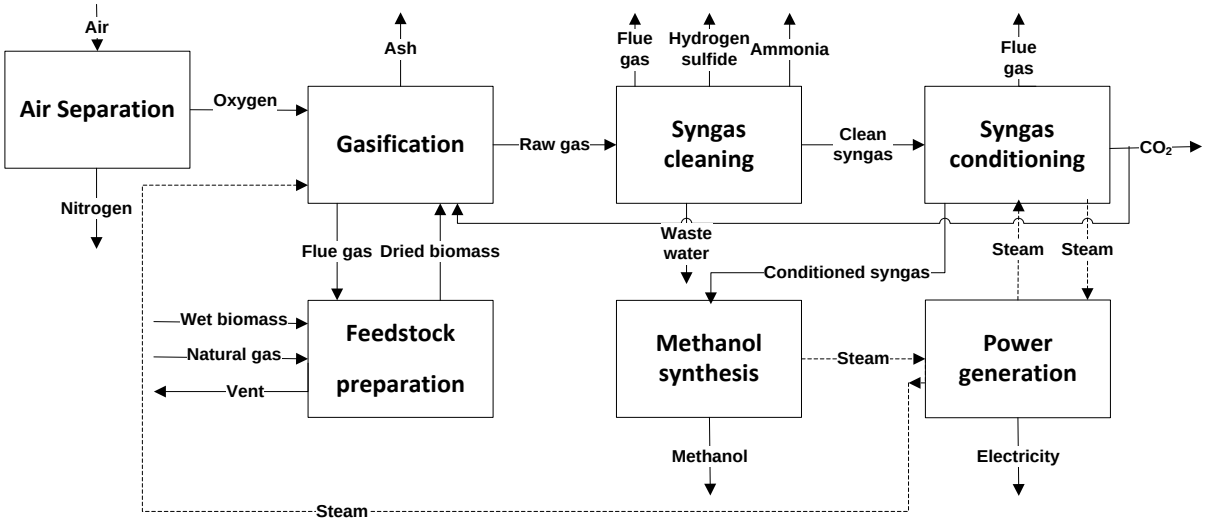

Fig.A.1: Overall process flow diagram of methanol synthesis [90]

[13] The sawmill residues are mixed bark and sawdust from softwood and hardwood

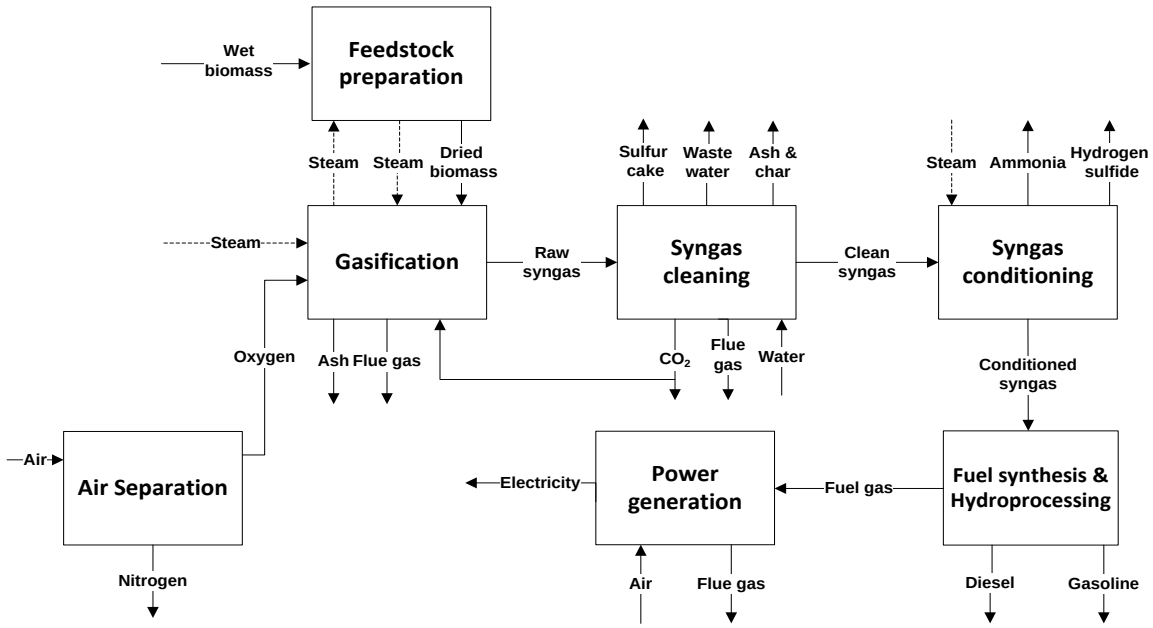

Fig.A.2: Overall process flow diagram of F-T diesel synthesis [3]

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CHAPITRE 6 ARTICLE 3: OPTIMAL DESIGN OF AN INTEGRATED BIOREFINERY SUPPLY CHAIN IN EASTERN CANADA: EXAMPLE OF BIOMETHANOL PRODUCTION IN PULP MILLS

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6.1 Abstract

Biorefineries integrated into pulp and paper mills are an attractive option to produce biofuels, reduce greenhouse gas emission and generate additional profit for the pulp and paper industry. The objective of this study is to quantify available biomass from fire-damaged stand, logging residues and sawmill residues and to propose an optimization model for the design of the integrated biorefinery supply chain. The proposed model determines the integrated biorefinery locations and capacities as well as the feedstock type. It has been applied to a case study of biomethanol production in Eastern Canada. Results indicate that the integrated biorefineries located in Eastern Canada can produce about 13 Mt y^{-1} of biomethanol and are located in Ontario and Quebec with a production cost range of 602 \$ t^{-1}- 641 \$ t^{-1}. Moreover, the operational constraint involves the implementation of additional integrated biorefineries. In this case, the biomethanol production cost increases by 35 %.

Keywords: Biofuel, cost-benefits analysis, logging residues, fire-damaged stand, supply chain optimization.

6.2 Introduction

Global demand for renewable bioenergy and associated services, to meet social and economic development and improve human welfare and health, is increasing. Bioenergy currently provides about 10 % of the global primary energy supply, and accounts for roughly 80 % of the energy derived from renewable sources [104].The global wood-based bioenergy market is increasing driven by the twin policy drivers of mitigating greenhouse gas (GHG) emissions and improving energy security.

In responses to fossil fuel prices volatility and social concern about climate change, Canada's energy sector is looking at strategies to expand the sustainable mobilization of biomass towards bioenergy production. For example, the renewable fuel policy [105], announced in 2007, stated that at least 5 % of the gasoline demand (estimated at 175 Mt annually) and 2 % of the diesel demand based on the volume (estimated at 222 Mt annually) should be supplied from renewable fuels to meet requirements both in terms of future fossil fuel consumption and reduction of GHG emissions [106].

In observance of these national regulations, policy and investment decisions on biorefining activities have targeted agricultural biomass as major feedstocks since they can be harvested, stocked and transformed into biofuels in a cost-effective manner [107]. However, the social and environmental advantages associated with agricultural biomass are controversial. This is mainly due to the direct competition of crops with food and animal feed and the fossil energy-intensive nature of agricultural feedstocks production [108, 109]. This 'food, energy, and environment trilemma" is a long-standing, controversial debate in the bioenergy literature [110, 111].

Many of the negative impacts associated with the use of 'first generation' biofuels produced from edible crops, can be circumvented with the use of lignocellulosic biomass available in non-edible plant parts to produce 'second generation' biofuels. This alternative stream of biomass sources include mainly agricultural waste residues, forestry resources and dedicated energy crops.

Lignocellulosic biomass derived from forestry resources is an abundant feedstock not used for human food and requires less fossil fuel to grow and collect than agricultural feedstocks [109]. With about 347 million hectare of forest land, the Canadian forest sector benefits from three large and stable sources of forest feedstock for wood-based biofuel production [112]. These include

logging residues (LR), which are by-products of harvesting operations (such as tree tops, branches, bucking and trimming materials, pruning, and small trees from early thinning) and secondary forest residues (processing residues), which are by-products of the industrial processing of wood, such as sawdust, wood shavings and wood chips. A third abundant and untapped forest feedstock for the production of renewable bioenergy is the salvage logging of standing dead or damaged trees resulting from natural disturbances such as wildfires, insects and disease [113-115]. About 0.72 million hectares of forest were harvested in 2014, 20.3 million hectares were damaged by insects and about 3.9 million hectares were burned in forest fires [112]. Even though a significant percentage of processing residues is already used mainly for pulp chips, wood composites, and pellets production, most of the LR as well as fire-damaged stand (FDS) are underutilized, especially in Eastern Canada (comprising New Brunswick, Newfoundland and Labrador, Nova Scotia, Ontario, Prince Edward Island and Quebec) [98]. On the other hand, the continuous decline of demand and activity in segments of the pulp and paper sector, have generated considerable interest, particularly within pulp mills (PM), to upgrade biomass and unused forest residues for the production of bioenergy as well as other bioproducts in order to become more competitive. The forest sector in Eastern Canada is, in particular affected by adverse impacts of both natural disturbances and sector decline. Therefore, in this study we aim at identifying the opportunities of mobilizing FDS and LR as primary feedstock to supply an integrated biorefineries in Eastern Canada.

The implementation of an integrated biorefineries into an existing PM that valorizes forest residues into renewable fuels could be an attractive option to satisfy the Eastern Canadian needs in terms of biofuels production, and GHG emissions reductions and to also to diversify the products basket of the PM in order to create additional profits [56, 116, 117].

Integrated biorefineries are facilities that use biomass conversion processes and equipment to produce any combination of renewable fuels, power, heat, steam, and chemicals from biomass through integration into existing processes, infrastructure and utility systems [118, 119]. There is a variety of biorefining technologies that can be integrated into an existing PM. These technologies are classified into biochemical and thermochemical platforms [120]. The biochemical process uses acid or enzymes to release sugars from biomass. Sugars can then be fermented to generate a variety of biofuels and biochemicals. Unlike the biochemical process, the thermochemical conversion technologies use pyrolysis or gasification to produce valuable products, including syngas, bio-oils, and solid char. These products can be recovered and further processed into products including biofuels (bioethanol, biobutanol, biomethanol, biodiesel, etc.), biochemicals and bioplastics similar to petroleum derivatives and compatible with the existing petroleum refining operations [121].

Processing lignocellulosic biomass like forest biomass in an integrated biorefinery based on the gasification technology could be an attractive option from an economic and environmental perspective for the pulp sector in Canada. In fact, integrated biorefinery could represent an emerging opportunity for PM that could expand their revenues and maintain their viability by diversifying their products portfolio since the scope of biofuels are wide ranging [42, 56, 116, 117, 122]. On the other hand, the syngas produced from the gasification process could substitute fossil fuel used in the PM that make the entire complex a fossil fuel free facility [56, 72]. Furthermore, development of integrated biorefineries through the gasification process to produce biomethanol could contribute to satisfy the Eastern Canadian biofuel target of 5 % (estimated at 6.5 Mt y^{-1}) set by the renewable fuels regulations. Partly due to the abundant resources of

biomass in the Eastern Canada, an even more challenging target of 10 % biomethanol in gasoline can be met [105].

Despite viability of gasification-based conversion technologies and abundant availability of underutilized forest biomass such as LR, and FDS, there is no commercial facility operating in Eastern Canada that utilizes such feedstock to produce biomethanol as a gasoline additive in an integrated biorefinery [123]. Knowing that to ensure the economic profitability of the integrated biorefineries, it is essential to establish and optimize its supply chain [124-126]. This study deals with the design of the integrated biorefinery supply chain in order to satisfy the Eastern Canadian biomethanol targets of 6.5 Mt y^{-1} and 13 Mt y^{-1} in a competitive price. The objectives are to: 1) quantify and locate available biomass from three different sources of feedstock which are FDS, LR and sawmill residues (SR), 2) find the optimal design of the integrated biorefinery supply chain that simultaneously predicts the optimal integrated biorefinery locations, the biomass selection, the production capacities and establish the allocation of biomass to integrated biorefineries and 3) determine the optimal biomethanol production cost including the costs for feedstock supplying, forest biomass treatment (processing), biomass transportation, production plant investment and operation, and methanol transportation. To meet these objectives, an approach that inputs spatial-explicit biomass data into a mixed integer linear programming (MILP) model developed using the General Algebraic Modeling System (GAMS) was proposed. The model was developed to consider several feedstocks, different forms of forest biomass as well as spatial distribution of feedstock supply and methanol demand locations. The developed model was analyzed under different resource, operational and demand scenarios such as proportion of sawmill residues and forest biomass availability, biomass procurement radius and biomethanol demand.

6.3 Material and methods

The biomass supply chain model was designated with the objective to minimize the total annual cost of biomethanol production in Eastern Canada as a whole. The supply chain model decides on the location, amount, and allocation of different types of feedstock to integrated biorefineries within a forest industry network, including PM sawmills and petroleum refineries.

6.3.1 Feedstock description and availability

In this study, three potential feedstocks are considered; LR, FDS and SR from wood processing. LR are composed of tree tops and branches as well as breakage, refused logs and bolts [98]. At the time trees are processed, LR are collected either at the forestside or at the roadside, depending on the harvesting method [28]. Three different harvesting methods can be used, namely: Cut-to-length (CTL), Full-Tree (FT) and Tree-length (TL) methods [81]. Approximately 90 % of harvest operations in Canada use the FT method [27], for this reason, only LR from FT harvesting system are considered to be modeled in this paper. With the FT method, trees are felled by a feller-buncher keeping branches and top intact. The full trees are then moved to the roadside using a cable, grapple or clam-bunk skidders where they are delimbed and topped. The LR generated, left on the forest roadside, can further be treated or transported directly depending on the processing system selected [81].

In order to supply forest biomass feedstock to the integrated biorefineries in the most cost effective way, three biomass procurement options, including two processing methods, namely grinding and bundling, are selected. LR could be (i) transported in uncomminuted form and then transformed into hog fuel (HF) by a stationary grinder at the mill-side (Uncomminuted LR form) , (ii) grinded at the roadside using mobile grinder and then transported in HF form to the mill-side

(Grinded LR form) or (iii) bundled at the roadside and further grinded in the mill-side (Bundled LR form).

The main advantage of roadside treatment either by grinding or bundling is to improve the bulk density of biomass and therefore to reduce the biomass transportation cost. However, this implies additional costs depending on the treatment method. There is then a critical decision to be made whether to treat the biomass at the forest landing or at the roadside.

Another abundant and untapped forest feedstock considered for the production of biomethanol is the FDS. It is estimated that 290.000 hectares per year in average were burn in the boreal forest of Eastern Canada between 1970 and 2010 [127]. After forest fires, dead trees are usually left standing and their wood starts to dry. Salvage harvesting of FDS is performed using similar equipment as regular roundwood (harvester, feller buncher) but only the stems are skidded to the roadside for further treatment or for transportation.

For this biomass type, two procurement options are investigated. FDS could be grinded at the roadside and transported as HF (Grinded FDS form) or hauled in loose form and further grinded at the mill-side (Uncomminuted FDS form). Bundling has not been considered as a processing option since the bulk density of the FDS is higher than that of bundles. It should be noted that this study does not consider chipping alternative since it cannot treat contaminated biomass and bundles [128].

SR from processing of lumber in the forms of barks, sawdust, and shavings are considered. Although, those feedstocks are widely utilized in Eastern Canada to produce particle board, electricity and pellets, more interesting bioproducts based on these resources have to be

investigated [129]. Chips are not considered since they have an established market in the pulp and paper industry.

LR and FDS availabilities were estimated by using the same approach from Mansuy et al. [98], the estimation of the theoretical biomass availability from LR (tree tops and branches) and FDS was computed by overlapping spatial datasets of forest attributes and forest disturbances both at a 250-m MODIS grid resolution and covering the Canadian forest land base. The first dataset provides spatially explicit quantities of aboveground biomass in forest stands, measured in mean pixel-level oven-dry metric tonnes per hectare (ODT ha^{-1}), and sorted by species and by tree compartment (branches, stems, bark and foliage) for the year 2001. The second dataset uses regression and decision-tree models with MODIS imagery to detect pixels affected by harvesting (clearcut only) and wildfires every year from 2001 to 2011, and also gives the fraction of the pixels affected by these disturbances. The robustness of both remote sensing products has been demonstrated and used in recent studies. For the first dataset, the accuracy of biomass estimates using an independent validation dataset was on average about 70 % and for the second dataset, the accuracy of detection of burnt and harvested wood was 82 % and 80 %, respectively. By overlaying the 2001 maps of forest properties and the maps of harvest and fire for years 2002-2011, we were able to calculate for each pixel the annual amount of biomass generated by wildfire or by clearcut, by species and tree compartment and to attribute a specific year to each event.

Potential SR quantities have been estimated at 27 % of the input log volume based on the Natural Resources Canada model presented in the work of Krigstin et al [130]. Meanwhile, since SR are already used for pellets production, and in heat and power plants [28], this type of

feedstock is considered in this study as an alternative resource to complete the entire demand. As a result, only 20 % of the produced quantity is therefore considered.

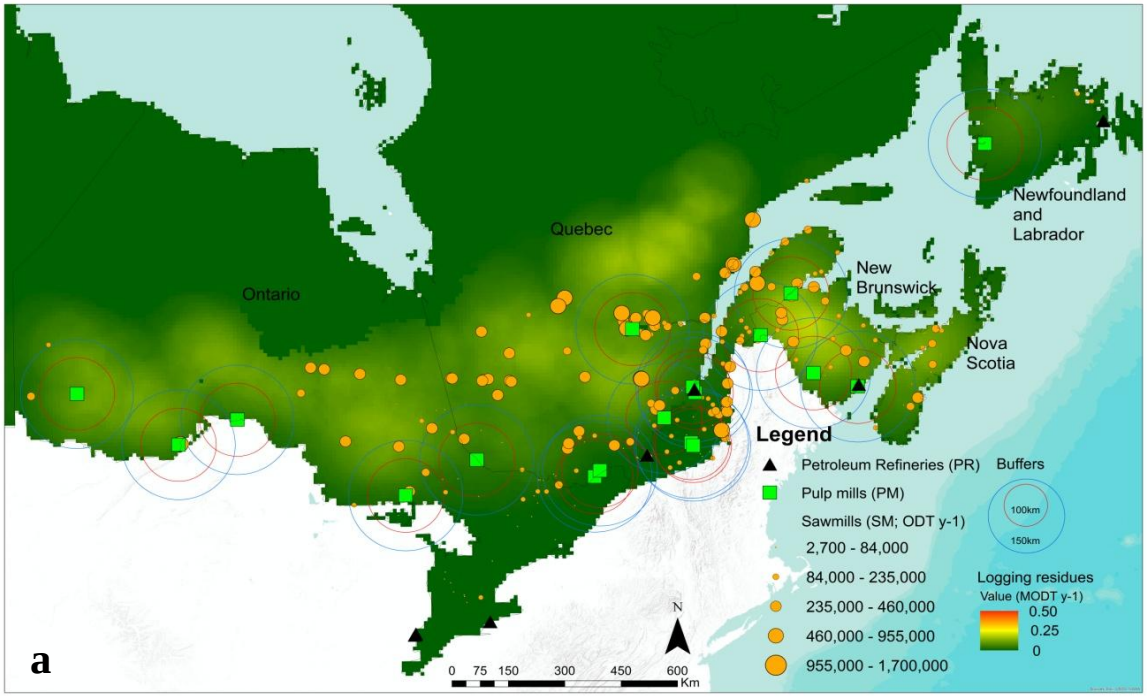
6.3.2 Supply chain network and design

Spatial locations of sawmills, PM and petroleum refineries have been identified in Eastern Canada (Fig. 6-1). As shown, the potential sites for biorefining activities could be integrated into 18 PM (9 in Quebec, 4 in New Brunswick, 4 in Ontario and 1 in Newfoundland and Labrador. The production capacity of each PM is obtained from their corresponding website (Table A.2). Each of those facilities uses natural gas to fire the lime kiln or to initiate the bark boiler. Natural gas consumption depends on the process used for the conversion of wood into pulp and the capacity of the mill. It is estimated at 1.8 GJ t^{-1} of pulp for thermochemical PM and 4.3 GJ t^{-1} for dissolving and Kraft PM [55]. The PM could then take advantage from the produced syngas in the integrated biorefineries to replace fossil fuel with a renewable fuel. The profits due to natural gas replacement are then considered in the economic optimization model developed in this study. The natural gas purchased cost is fixed at 2.85 \$ GJ^{-1} based on reference [75].

The biomethanol produced in the potential integrated biorefineries has to be distributed among eight petroleum refineries actually delivering fossil transportation fuels (Fig. 6-1) [106]. The biomethanol demand is fixed based on the refining capacities and the biofuel blending requirement (Table A.3 in the Appendix).

The biomass available from LR and FDS are estimated within two radii of distance from each potential integrated biorefinery site, 100 and 150 km using the buffer tool in the Geographic Information System Arcgis 10.0 (ESRI). The need to limit the harvesting distance is mainly to reduce the biomass transportation cost which is a predominant factor for the economic viability

of the integrated biorefinery supply chain [28]. The upper limit is fixed at 150 km based on studies showing that in Canada the economic distance for roadside forest residues generally does not exceed 150 km [28]. Table A.4 in the appendix shows the total estimated quantities of LR available in a radius of 100 and 150 km from the considered PM (20 Mt y^{-1} and 43 Mt y^{-1} respectively) are higher than those of FDS (7 Mt y^{-1} and 13 Mt y^{-1}).



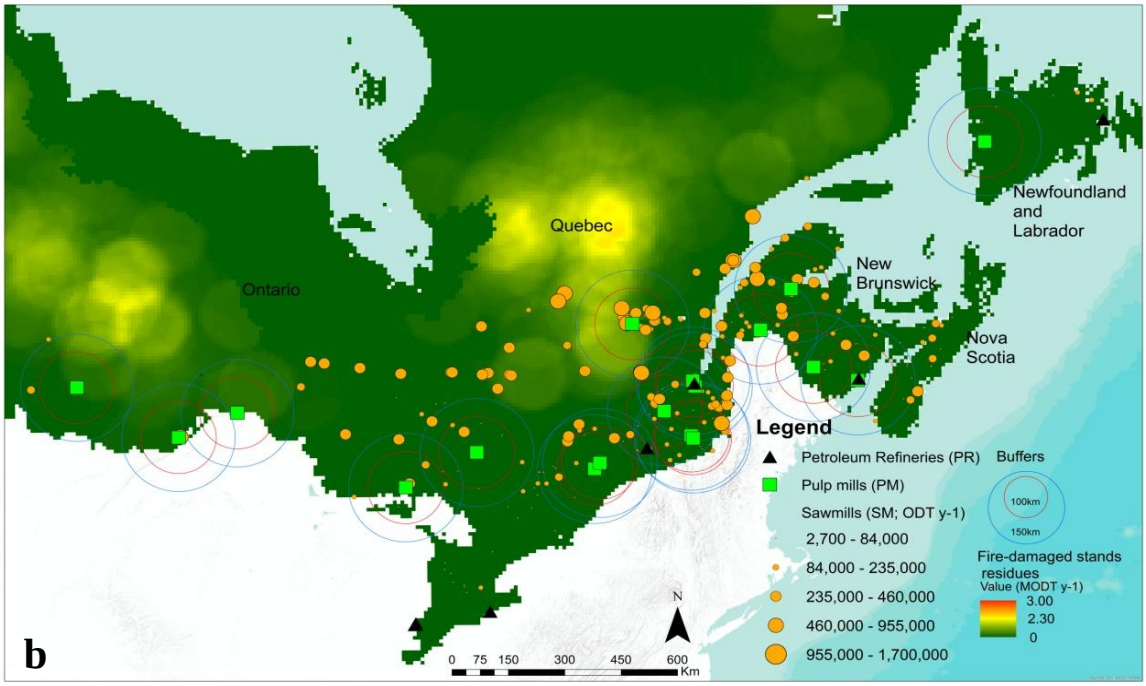


Figure 6-1: Spatial distribution of sawmills, pulp mills and petroleum refineries in Eastern Canada: (a) with biomass available (Mt y^{-1}) from logging residues and (b) with biomass available (Mt y^{-1}) from fire damaged stands

6.3.3 Feedstock supply procurement and cost

To haul biomass to the potential integrated biorefinery site, truck has been considered as the only transportation mode in the supply chain since the forest biomass sources are generally dispersed over large area. Moreover, for short transport distances, truck transport is the most competitive way of biomass transportation [82]. The biomass transportation cost is calculated based on the equations developed by Alam et al. [131] for the various biomass resources and forms and is shown in Table 6-1. The bulk densities, the moisture contents considered for the calculation of the biomass transportation costs as well as the others related parameters are given in Table A.5 in the appendix.

LR procurement costs are based on the studies undertaken by FPInnovations [28] and detailed in Table 6-1. The cost of LR procurement in uncomminuted form is estimated at 17 \$ t^{-1} which includes pre-piling, mill-side chipping costs at as well as roads construction, maintenance and forest management charges. LR chipped at the roadside and delivered to the integrated biorefinery as HF cost 20 \$ t^{-1}. Roadside bundling system is the most expensive option estimated at 24\$ t^{-1}. In this study, the wood harvesting cost including felling, forwarding and delimbing is allocated entirely to the primary forest products, lumber and pulp, and do not apply to forest residue costs [28]. We assume also that charges related to roads construction and maintenance assigned to the integrated biorefineries would be entirely refunded by the Canadian government to promote bioproducts and biofuels manufacturing. The total cost of harvesting biomass from FDS is estimated at 35 \$ t^{-1} (Table 6-1). It includes felling and skidding costs, road construction and overhead charges as well as forestry fees. Felling and skidding costs are obtained from the work of Gautam et al. [132] while the others cost components are based on data from Kumar et

al. [25]. Grinding cost is added to have the total FDS supply cost. It is estimated at 8 $ t^{-1} when comminution is done at roadside including loading to grinder [132] and 6 $ t^{-1} at mill-side [133] considering that one dry ton of FDS with 12 % moisture has a bulk density of 0.45 t m^{-3}. As for LR, the roadside construction and infrastructure fees are assumed to be refunded. The purchased cost of SR including sawdust, shaving and bark is estimated at 25 $ t^{-1} based on the work of Linkewich [134].

Table 6-1: Procurement and transportation costs of logging residues and fire-damaged stand ($ t^{-1})

Cost Components	**Unit cost ($ t^{-1})**	
Procurement costs of logging residues		
LR[15] pre-piling (for uncomminuted and hog fuel forms)	2.16	
Roadside LR grinding (for hog fuel form)	11.2	
Roadside LR collecting and bundling (for bundles form)	10.6	
Mill side bundles chipping (for bundles form)	4.5	
Mill side LR chipping (for uncomminuted form)	8.61	
Roads construction and use, forest management	6.41	
Harvesting fire-damaged stand cost		
Felling	6.2	
Skidding	4.9	
Forestry	6.2	
Roads construction, infrastructure	7.7	
Overheads	9.8	
Biomass transportation cost	**Variable cost ($ kt^{-1} km^{-1})**	**Fixed cost ($ kt^{-1})**
Uncomminuted LR	0.22	38
Grinded LR	0.05	8.7
Bundled LR	0.10	18
Uncomminuted FDS[16]	0.04	6.8
Grinded FDS	0.02	4.1
SR[17]	0.03	5.6

[15] Logging residues

[16] Fire-Damaged Stand

[17] Sawmill residues

6.3.4 Biomethanol production process and costs

In this study, biomethanol is obtained though a thermochemical process, where biomass is firstly pre-treated depending on its initial form (biomass is sent in uncomminuted form, as hog fuel, bundles or fine particles). Biomass is then gasified and the syngas containing CO and H_2 is fed to the conventional methanol synthesis process. The process configuration considered in this study is adapted from the Tennessee Valley Authority report [80]. It involves the following processing steps: biomass pre-treatment, gasification, gas cleaning, conditioning, conversion, product separation and power generation. Biomethanol can be blended with gasoline or further refined to other biochemicals such as dimethyl ether, formaldehyde, acetic acid, ethylene, gasoline, etc [135].

To calculate the total capital investment cost, four production capacity levels have been defined. The upper capacity level is fixed at the total biomethanol demand. The upper and lower purchased equipment costs related to each capacity interval are calculated using Equation 1.

$$Cost_l = Cost_r . (Q_l / Q_r)^R$$

Where R is the scaling factor, it is assumed to be 0.7 [73]. Cost $_l$ and Cost $_r$ are the purchased equipment costs for two plants with different capacities, l and r.

The biomethanol purchased equipment costs for 0.31 Ml y^{-1} reference capacity are presented in Table 6-2. All costs are reported in 2015 Canadian dollars. The purchased cost of equipment related to the capacity level is the average of the upper and lower costs. The total purchased equipment cost (TPEC) for a capacity level is obtained by summing all the purchased equipment costs. The capital investment cost related to each capacity level can be calculated from the total purchased equipment cost based on data from Swanson et al. [3]. The installation factor is fixed

at 2.75 as assumed in [73]. To account for economy of scale, the Total Investment Cost (TIC) of the integrated biorefinery has been expressed by an interpolated piecewise linear cost curve for each capacity level as given in Equation 18. The TIC has been annualized using Equation 19.

Truck is also considered for biomethanol transportation. Related cost data are obtained from the work of You & Wang [136]. Variable and fixed biomethanol costs are 4.25E-04 \$ l^1 km^{-1} and 3.28E-04 \$ l^{-1}, respectively.

Table 6-2: Summary of purchased equipment costs for biomethanol process synthesis (M\$). Costs estimated in Canadian dollars

Process unit	**Cost (M\$)**
Air separation	3.5
Feed handling and drying	3.7
Gasification	11.4
Syngas cleaning & conditioning	2.1
Biomethanol synthesis & separation	9.4
Power generation	1.2
Balance of plant	4.7
Total	36

6.3.5 Model formulation

An optimization model was developed to locate, size, and allocate biomass to the integrated biorefineries in order to meet the total biomethanol production target of 5 % by volume of the current gasoline demand (about 6.5 Mt y^{-1}) in a cost-effective manner. The model considers several biomass feedstocks (LR, FDS, SR) and forms (uncomminuted, grinded and bundled biomass) as well as spatial distributions of feedstock supply (forest biomass and SR), receptor PM and PR.

Decisions integrated into the model are whether to build an integrated biorefinery in a given PM 'k' from forest biomass '$Yb_{b,i,k}$' or from SR '$Ys_{j,k}$'; if built, what is the capacity of the integrated biorefinery 'cap_k', which sawmills 'j' are considered, how much SR are shipped, '$Ssr_{j,k}$', what type of forest biomass is used and how much is procured '$Sfb_{b,i,k}$' and finally which petroleum refinery 'l' are served '$Tm_{k,l}$'. The set 'b' corresponds to the forest biomass resources in their different forms, 'i', 'j', 'k' and 'l' represents the locations of biomass procurement sites, sawmill sites, PM and PR, respectively.

The constraints of the model are represented by Equation 2 to Equation 14.

According to Equation 2, the quantity of forest biomass supplied from 'i' to 'k' is constrained by the available amount and the recovery rate considered.

$$Sfb_{b,i,k} \leq Rc_{b,i} . Bq_{b,i} . Yb_{b,i,k} \quad \textbf{(2)}$$

Where $Sfb_{b,i,k}$ is the total forest biomass quantity supplied from site 'i' to the integrated biorefinery 'k','$Bq_{b,i}$' is the available amount of forest biomass 'b' in procurement site 'i' and '$Rc_{b,i}$' is the recovery rate of forest biomass 'b' in site 'i'.

The total quantity of SR supplied from 'j' to 'k' is constrained by the available amount in sawmill 'j','Sq_j', the average percentage of SR that can be shared, 'Rsr' (due to the growing competition between energy options such as wood pellet as well as heat and power [28]), and the minimum amount that should be recovered 'Msr'.

$$Ssr_{j,k} \leq Msr . Rsr . Sq_j . Ys_{j,k} \quad \textbf{(3)}$$

The capacity of the integrated biorefinery 'k' named 'cap_k', is defined by Equation 4

(4)

$$cap_k = \sum_p capr_{p,k}$$

Where $'capr_{p,k}'$ is an auxiliary variable introduced to allow the calculation of the investment cost of the integrated biorefinery in 'k' by an interpolated piecewise linear cost curve for each capacity level 'p'.

To model the selection of one capacity level 'p' in the integrated biorefinery 'k', a binary variable $'Yc_{k,p}'$ is introduced in Equation 5.

$$\sum_p Yc_{k,p} \leq 1 \quad \textbf{(5)}$$

The capacity of the integrated biorefinery 'k' with the capacity level 'p',$'capr_{p,k}'$, is limited by the lower and the upper capacities of the same capacity level 'p'.

$$Lo_p . Yc_{k,p} \leq capr_{p,k} \leq Up_p . Yc_{k,p} \quad \textbf{(6)}$$

From Equation 7, we assume that only one forest biomass type and form can be used in each integrated biorefinery 'k'.

$$\sum_{b,i} Yb_{b,i,k} = \sum_p Yc_{k,p} \quad \textbf{(7)}$$

The total biomethanol produced in integrated biorefinery 'k',$'Pm_k'$, is related to the total amount of biomass procured from 'i' and 'j' and the conversion efficiency of the biomethanol process,'Eff'. In this paper, it was assumed that the conversion factor for biomethanol synthesis is not affected by the capacity of the integrated biorefinery.

$$Pm_k = Eff\ .\ (\sum_{b,i} Sfb_{b,i,k} + \sum_j Ssr_{j,k}) \quad \textbf{(8)}$$

The biomethanol quantity transported from 'k' to the petroleum refinery 'l', $'Tm_{k,l}'$, should be equal to the biomethanol quantity produced in 'k',$'Pm_k'$.

$$Pm_k = \sum_l Tm_{k,l} \quad \textbf{(9)}$$

The total biomethanol produced in the integrated biorefinery 'k' should be comprised between the production capacity and the capacity utilization ratio.

$$Mp\,.\,cap_k \leq Pm_k \leq cap_k \quad \textbf{(10)}$$

'Mp' represents the minimum amount of biomethanol as a percentage of the production capacity.

The capacity of the integrated biorefinery 'k', $'cap_k'$, should be greater than the minimum plant capacity $'Mcap'$.

$$cap_k \geq Mcap\,.\sum_p Yc_{k,p} \quad \textbf{(11)}$$

The total biomethanol transported from the integrated biorefinery 'k' to the petroleum refinery 'l',$'Tm_{k,l}'$, should be greater than the biomethanol demand 'Demm$_l$'.

$$\sum_k Tm_{k,l} \geq Demm_l \quad \textbf{(12)}$$

To model the procurement of forest biomass within a fixed radius from each PM, constraints (13) and (14) are added.

$$Yb_{b,i,k} \geq diag_{i,k}\,.\,(1\text{-}diag_{i,k}) \quad \textbf{(13)}$$

$$Yb_{b,i,k} \leq diag_{i,k} \quad \textbf{(14)}$$

The total annual cost 'Tac ' presented by Equation 15 represents the objective function to minimize.

$$Tac = Aic + Bpc + Btc + Mpc + Mtc - Ngp \quad \textbf{(15)}$$

'Tac' is the sum of the costs associated with biomass procurement *'Bpc'*, biomass transportation *'Btc '*, production 'Mpc ', annualized investment cost *'Aic '* and biomethanol distribution *'Mtc '* minus the profit from natural gas substitution *'Ngp'*. The definitions of these terms are given by equations (16)–(22).

The biomass procurement cost *'Bpc '* is given by Equation 16:

$$Bpc = \sum_{i,b,k} Cb_{b,i} \,.\, Sfb_{b,i,k} + \sum_{j,k} Csr \,.\, Ssr_{j,k} \quad \textbf{(16)}$$

where *' $Cb_{b,i}$'* is the harvesting unit cost of biomass 'b' supplied from site 'i'.

The production cost *'Mpc'* depends on the size of the integrated biorefinery. It is defined as a sum of a fixed cost, dependent on the production capacity, and a variable cost expressed in terms of the quantity of biomethanol produced *'Pm_k'*.

$$Mpc = \sum_k \left(Vcp \,.\, Pm_k + Fcp \,.\, cap_k\right) \quad \textbf{(17)}$$

Where *'Vcp'* and *'Fcp'* are the variable and fixed production costs, respectively.

The total investment cost *'Tic'* is expressed by an interpolated piecewise linear cost curve for each capacity level 'p'. It is given by Equation 18:

$$Tic = \sum_{k,p} (Ic_{p-1} \,.\, Yc_{k,p}) + ((Capr_{p,k} - Lo_p \,.\, Yc_{k,p}) \,.\, (\tfrac{Ic_p - Ic_{p-1}}{Up_p - Lo_p})) \quad \textbf{(18)}$$

Where *'Ic_p'* is the investment cost of installing an integrated biorefinery with capacity level 'p', *'Up_p'* and *'Lo_p'* are the upper and lower bounds of the production capacity with capacity level 'p'.

The annualized investment capital cost is given by Equation 19:

$$Tac = \left(\frac{IR}{1-\frac{1}{(1+IR)expte}}\right).Tic \quad \textbf{(19)}$$

Where 'IR' is the interest rate and $'te'$ is the economical lifetime of the project.

The total biomass transportation cost is the sum of the fixed cost and distance dependant cost.

$$Btc = \sum_{b,i,k}(Fbtc_b + Vbtc_b \,.\, Dbr_{i,k}).Sfb_{b,i,k} + \sum_{j,k}(Fstc + Vstc \,.\, Dsr_{j,k}).Ssr_{j,k} \quad \textbf{(20)}$$

The total biomethanol transportation cost is calculated in the same manner than the biomass transportation cost.

$$Mtc = \sum_{k,l}(Fmtc + Vmtc.Drd_{k,l}) \,.Tm_{k,l} \quad \textbf{(21)}$$

Natural gas profit $'Ngp'$ depends of the natural gas cost $'Ngc'$ and the quantity avoided by replacing fossil fuel with syngas in the PM $'Nga_k'$.

$$Ngp = \sum_k Ngc \,.Nga_k \,.Yc_{k,p} \quad \textbf{(22)}$$

The biomethanol unit cost is calculated by dividing the total annual cost by the total demand.

The optimal design is determined by a MILP model. It is solved with the CPLEX optimization software using the GAMS modeling language. The list of defined sets, parameters, and variables is given in Table A.1 in the appendix.

6.3.6 **Scenarios parameters**

To minimize the total annual biomethanol production cost, six different scenarios have been evaluated according to the following parameters: the feedstock source, the biomass procurement radius and treatment systems (grinding, bundling), the operational constraint and the biomethanol

blending requirement (Table 6-3). The impact of the operational constraint is illustrated in scenarios S1a, S2a and S3a through the biomass recovery rate parameter. The low recovery rate is estimated at 52 % to reflect the current operational conditions [137]. The same percentage is chosen for FDS and LR feedstock as similar operational constraints could limit the amount of available biomass; however, there is no constraints applied to the SR.

6.4 Results

6.4.1 Optimal design of the integrated biorefinery supply chain

The optimization has selected forest biomass grinding at the roadside before transportation as the optimal treatment method whatever the scenario considered and the type of biomass (LR, FDS). This method provides the best trade off in terms of biomass transportation and procurement costs.

The optimal locations of the potential integrated biorefineries are presented in Fig.6-2. The letters and figures near the selected PM represent the scenario considered and the biomethanol production capacity that have been selected at a given integrated biorefinery. The percentage of each biomass feedstock used to satisfy the entire demand is shown in Fig.6-3.

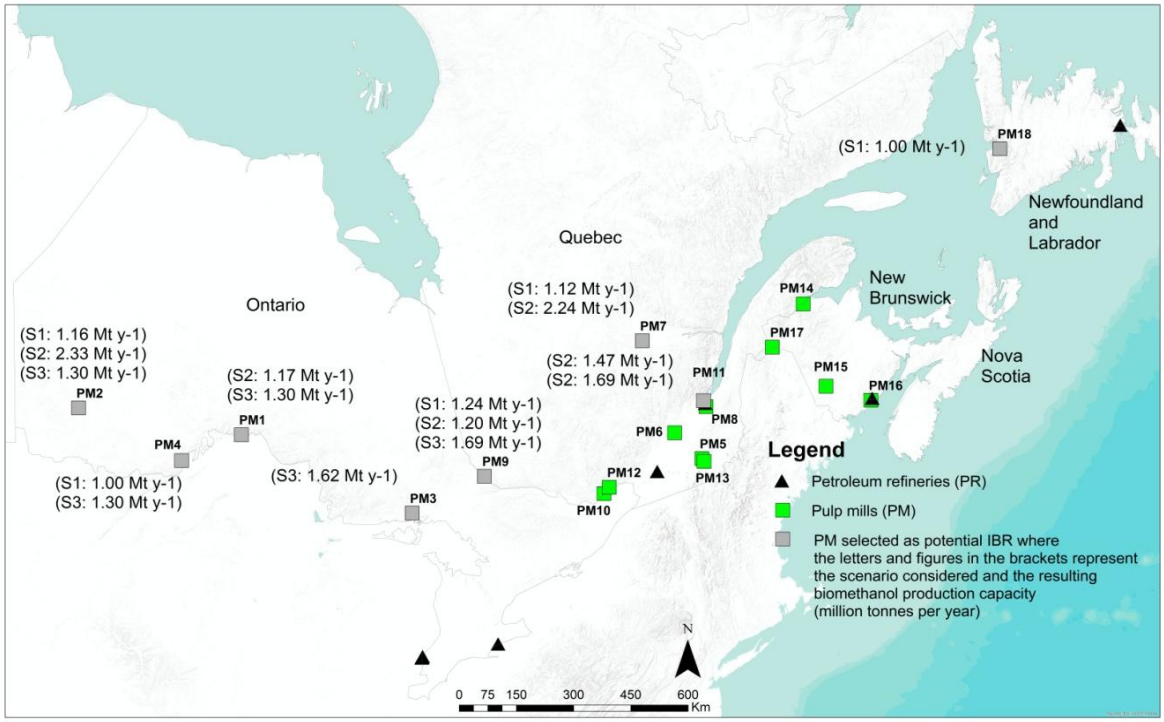


Figure 6-2: Optimal locations of the potential integrated biorefineries for each scenario without operational constraints and the resulting biomethanol production (Mt y^{-1})

Table 6-3: Definition of the scenarios

	Type of feedstock (LR, FDS and/or SR)	Procurement radius (in km distance from the forest)	Biomass recovery rate (in % of biomass available)	Blending requirement (in % of total gasoline demand)
Scenario 1.a: low blend, short distance, full recovery	LR (3 procurement options: ULR, GLR or BLR form)	100	100%	5%
Scenario 1.b: low recovery instead	FDS (2 procurement options: UFDS or GFDS form) SR (20%)	100	52%	5%
Scenario 2.a: low blend, longer distance, full recovery	LR (3 procurement options: ULR, GLR or BLR form)	150	100%	5%
Scenario 2.b: low recovery instead	FDS (2 procurement options: UFDS or GFDS form) No SR	150	52%	5%
Scenario 3.a: higher blend, longer distance, full recovery	LR (3 procurement options: ULR, GLR or BLR form)	150	100%	10%
Scenario 3.b: low recovery instead	FDS (2 procurement options: UFDS or GFDS form) SR (20%)	150	52%	10%

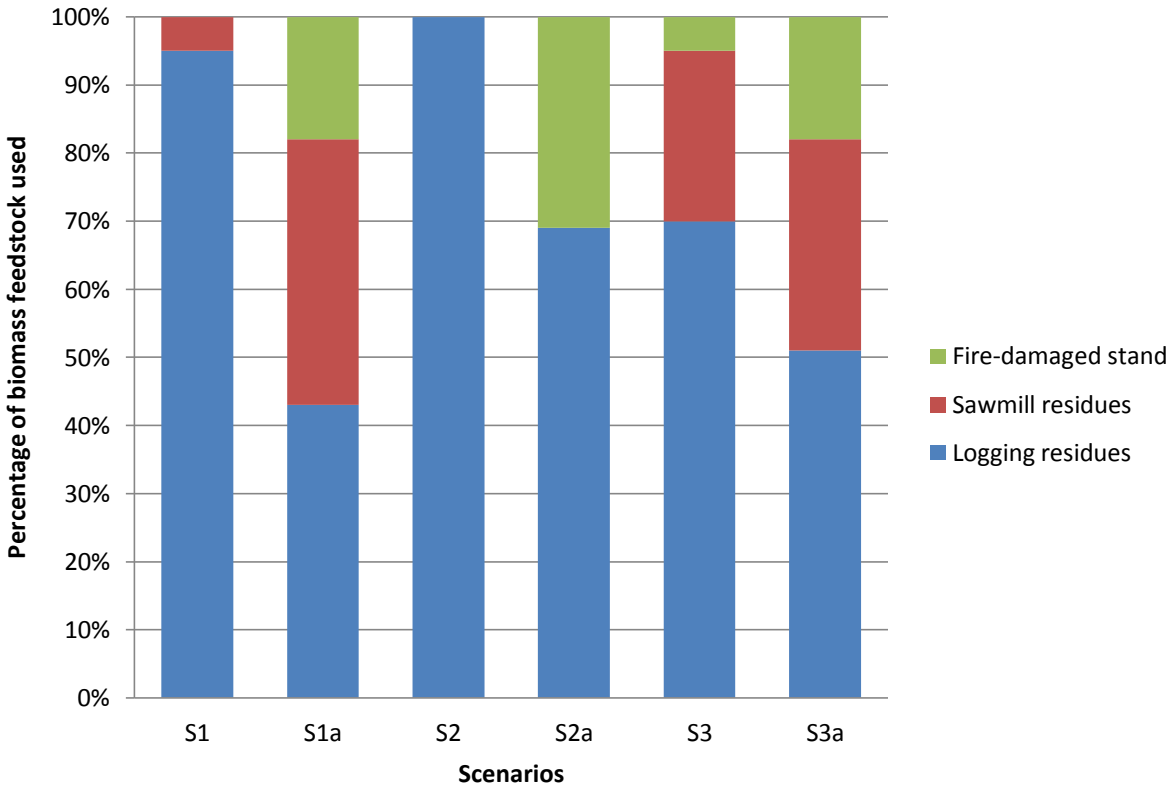


Figure 6-3: Percentage of biomass feedstock used to satisfy the entire demand in biomethanol production

The scenario S1 identified six potential integrated biorefineries, located in Ontario (PM2 and PM4), Quebec (PM6, PM7 and PM9) and Newfoundland and Labrador (PM18). The production capacity varies between 1 Mt y^{-1} to 1.24 Mt y^{-1} which is limited by the biomass available within a radius of 100 km from the receptor PM and the distances between the PM and the petroleum refineries. In this scenario, 95 % of the produced biomethanol is generated from LR whereas the 5% remaining is obtained from SR.

For scenario S2, six potential integrated biorefineries namely PM1 and PM2, located in Ontario, and PM6, PM9, and PM11 situated in Quebec are identified. With a radius of 150 km, the production capacity varies between 1.12 Mt y^{-1} and 2.33 Mt y^{-1}. This scenario uses 100 % of

LR as the integrated biorefineries are integrated into PM where there are abundant resources of LR. Using only forest biomass, a smaller distributed network structure in terms of number of integrated biorefinery plants and biomass procurement sites is identified.

Eight optimal integrated biorefineries are identified in scenario S3. By increasing the biomethanol blending requirement to 10 % (production level of about 12.9 Mt y^{-1}), the production capacity varies between 1.30 Mt y^{-1} to 2.24 Mt y^{-1}. Most of the integrated biorefineries identified are similar as for scenario S2 (PM1, PM2, PM6, PM9, PM11), however, three additional plants are added in Ontario (PM3, PM4) and Quebec (PM7). In this scenario, SR and FDS have been used to fulfill the entire demand. In fact, 70 % of the produced biomethanol is produced from LR whereas the remaining is generated from SR and FDS with respectively 25 % and 5 %. The integrated biorefinery located in PM2 is the only plant using FDS feedstock.

6.4.2 Effect of the operational constraint on the optimal design of the integrated biorefinery supply chain

Operational constraints affect significantly the location, the number of eligible integrated biorefineries and their capacities (Fig.6-4). For scenario S1a, the production capacity varies between 1.1 Mt y^{-1} and 1.74 Mt y^{-1}. The integrated biorefineries located in Ontario (PM2, PM4) and Quebec (PM7) remained unchanged compared to S1, however, PM6, PM9 and PM18 are replaced by PM14 and PM15, both located in New Brunswick (Fig.6-4). In this scenario, 43 % biomethanol is produced from LR, whereas the remaining is produced from SR and FDS with respectively 39 % and 18 %. The integrated biorefinery implemented in PM7 is the only plant which uses 100 % FDS as forest biomass.

For scenario S2a, the integrated biorefineries located in PM2, PM7, PM14, PM15 remain unchanged compared to S1a, however, PM4 are replaced by PM17 located in New Brunswick. The production capacity varies between 1.1 Mt y^{-1} and 2.19 Mt y^{-1}. One should notice that considering operational constraints in this case does not affect the capacity to satisfy the entire demand even if SR are not considered. The reason is that important biomass quantity is available within a radius of 150 km from the selected PM. As most of the selected integrated biorefineries use 100 % LR, except for the integrated biorefinery implemented in PM7, which uses exclusively FDS. Of the total, 69 % of the produced biomethanol in this scenario comes from LR, whereas the remaining is produced from FDS.

By increasing the gasoline-blending requirement to 10 % in scenario S3a, additional smaller size integrated biorefineries are added in Quebec (PM9 and PM11) to fulfill the entire biomethanol demand. The production capacity varies between 1.31 Mt y^{-1} and 2.88 Mt y^{-1}. In this scenario, 51 % of the produced biomethanol comes from LR whereas the remaining is generated from SR and FDS with respectively 31 % and 18 %. The integrated biorefinery located in PM7 is the only plant using FDS feedstock.

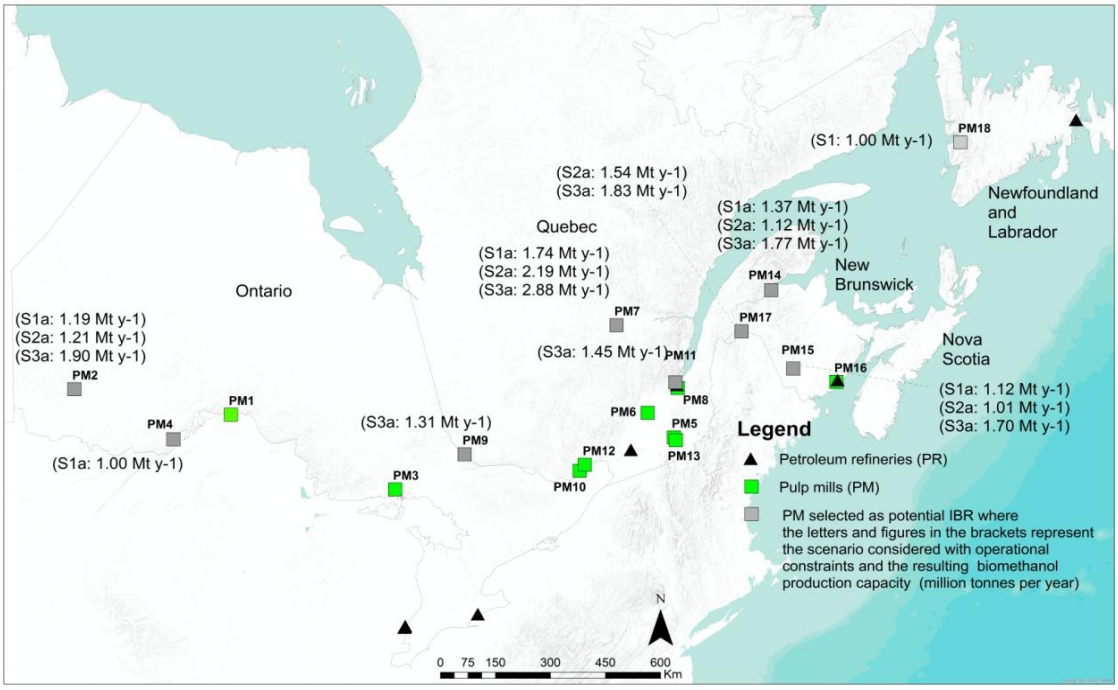


Figure 6-4: Optimal locations of the potential integrated biorefineries for each scenario tested with operational constraints and resulting biomethanol production (Mt y^{-1})

6.4.3 **Biomethanol production cost**

The optimal unit cost of biomethanol is sensitive to operational constraints; however, it does not change significantly with the other scenario parameters such as procurement radius and blending requirement (Fig.6-5). For scenarios S1, S2 and S3, the optimal unit cost varies little, between 602 \$ t^{-1} and 641 \$ t^{-1}. The range of values is larger for scenarios S1a, S2a and S3a since the optimal unit cost goes from 841 \$ t^{-1} to 939 \$ t^{-1}. In general, by considering operational constraint, the optimal unit cost increases by about 45 %. As can be seen from the costs breakdown of the scenarios, the biomethanol transportation cost is the major cost. It passes from about 39 % of the optimal unit cost for scenarios S1, S2 and S3 to about 55 % for scenarios considering operational constraint. This is relevant since by considering operational constraints,

the optimal integrated biorefinery locations are modified to satisfy the entire demand. Biomethanol is then hauled over longer distances to serve the entire PR. On the other hand, the annualized investment cost remains constant for all scenarios except for scenario S3a where it is increased by 16 % since additional integrated biorefineries have to be implemented to satisfy the entire demand. The biomass transportation cost part is significantly low as a limited procurement radius is assumed in this article. However, it is slightly higher for scenarios where SR are considered. Costs related to biomass procurement and biomethanol production remain stable in all the considered scenarios. Not that by substituting natural gas with syngas in the lime kiln and bark boilers of the PM, a net saving of 2 \$ t^{-1} is achieved for all scenarios.

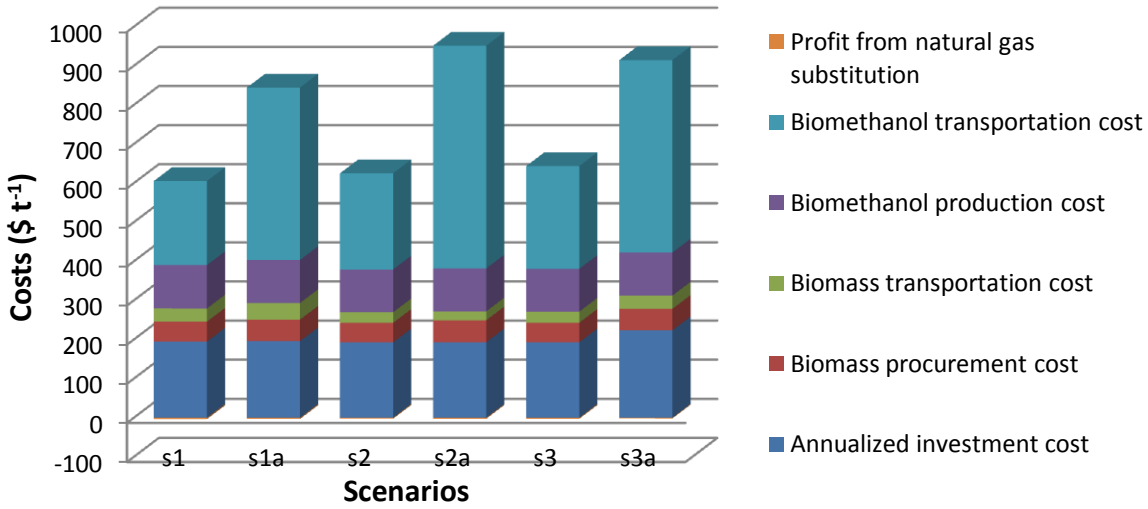


Figure 6-5: Breakdown of the unit biomethanol production cost for each scenario

6.5 Discussion

The objective of this study was to quantify the available biomass from three sources of feedstock (fire-damaged stand, logging residues and sawmill residues) and to propose a system optimization framework for the optimal design of the integrated biorefinery supply chain to

minimize the total annual biomethanol production cost. Coupling the geographic information system model with a mixed integer linear programming optimization model allows assessing a wide range of scenarios and testing sensitivity to changes in feedstock type, plant capacity and demand. The optimization model was developed to simultaneously predict the optimal network design, the integrated biorefinery locations and capacities, and the biomass type and forms, while minimizing the annual biomethanol production cost.

The results show that the forest sector in Eastern Canada has the potential to produce 13 Mt y^{-1} of biomethanol, which is sufficient to attain the amount of biomethanol needed for 10 % gasoline blending. The results also suggest that the type of feedstock that is mainly consumed in Eastern Canada to produce biomethanol is the LR. Additionally, FDS and SR could be used to fulfill the demand when LR become fully exploited. Overall, 58 % of the biomethanol is produced from LR, 20 % from DW and the remaining is from SR. This is due to the high concentration of LR available within a radius of 150 km from the existing PM, compared to FDS (42 Mt y^{-1} and 13 Mt y^{-1} respectively) and the procurement cost associated with this forest biomass. Valorizing mostly LR offers more stable supply chains. Although little used in our models (less than 15% on average),the use of FDS could however make supply chains riskier in terms of long-term stability and logistics as this type of biomass feedstock is more uncertain due to the variability of wildfires in time and space [98, 138, 139]. The supply risk of FDS can be mitigated since various biomass feedstocks are considered. In fact, according to the work of Golecha and Gan [140], year to year feedstock supply variability can be managed by developing an adequate biomass diversification strategy [140, 141]. Others approaches can be used to manage forest biomass supply risk, mainly storage and pre-treatment strategies [136, 142]. The advantage of the biomass diversification

strategy is to avoid the higher costs and the additional infrastructural requirements related to storage and pre-treatment approaches.

Our model results show that, without considering operational constraint, most of the integrated biorefineries are concentrated in the provinces of Quebec and Ontario. These forest-rich provinces represent the optimal regions for biorefining activities with the highest production capacity. This is explained by the fact that the majority of pulp mills are located in Quebec and Ontario, corresponding with the geographic distribution of forest fiber in the Eastern Canada and since these provinces have already an established petroleum industry networks. Such results may explain why the Quebec government has established a forest biomass action plan to encourage efforts to build advanced biofuel plant and to add value to forest resource by establishing targets and funding for cellulosic biofuel production in the province [143, 144]. The Ontario government has also encouraged efforts to transform the forest industry in order to create new activities and to develop new products by offering financial incentives and funding [145].

By introducing operational constraints, additional integrated biorefineries are added in New Brunswick, since the biomass economically available in Ontario and Quebec becomes fully exploited. The important area of private land in New Brunswick enables this province to increase the supply of forest biomass in the long-term through sustainable forest management activities or through the development of energy crops. In fact, along with Quebec and Ontario provinces, the New Brunswick government is in the process of reforming its forest tenure system to allow access to wood for new markets and to allow flexibility for the sector. For example, each of the three provinces has passed legislation to free up residual forest biomass comprising small diameter wood and tree branches and crowns. In the past, residual wood has been left in the forest

and the private companies that held contracts over the forest did not permit others to use it. The passed legislation allows the provinces to valorize this residual biomass into biorefining products.

Moreover, as a result of the significant drop in the pulping capacity in New Brunswick, excess wood chips at sawmills will be available in the near-term [146, 147]. With the new forest tenure reform and the surplus of biomass potentially available, it is very likely that the potential integrated biorefineries in New Brunswick might have greater biofuel capacities.

The results of the economic analysis show that the optimal production cost of biomethanol ranged from 602 \$ t^{-1} to 641 \$ t^{-1} without considering operational constraints. Enlarging the biomass procurement radius and increasing the blending requirement did not have a significant impact on the optimal production cost. The reason is that in this study, the capacity of the integrated biorefinery is limited by the supply potential of its procurement area. In fact, we cannot benefit from the economy of scale in the case of larger conversion plants due to the maximum capacity limits of feedstock procurement. Under a supply chain including pre-processing depots, biomass procurement radius could be extended since the biomass hauling cost is reduced. Cost advantages can then be achieved with larger biorefineries. Many studies have been carried out to determine the optimal size of the biorefinery considering the tradeoffs between the advantages of larger plants and the increased costs of hauling more biomass feedstocks over longer distances. Aden et al. [148] demonstrated that by increasing the quantity of biomass available, a net savings of 0.016 \$ could be achieved with an optimal plant capacity of 1.8-2.4 Mt y^{-1}. Hamelinck et al. [149] investigated the economics of a biorefinery with 0.6, 1.5 and 3 Mt y^{-1} of lignocellulosic biomass capacity and concluded that the implementation of a conversion facility with a capacity higher than 3 Mt y-1 is not economically viable. Furthermore,

Carolan et al. [150] indicated that biomass capacities of 1.4-2.7 Mt y^{-1} are required to achieve process economies. On the other hand, Wright & Brown [151] established the optimal size of different types of biorefineries. They estimated that biorefineries producing transportation fuels from lignocellulosic biomass are optimally sized in the range of 2.3–3.9 Mt y^{-1}. Finally, Leboreiro & Hilaly [152] demonstrated that the optimal plant size for biorefineries producing bioethanol from agriculture waste is about 1 Mt y^{-1}. However, by introducing operational constraints, the modifications in the network configuration significantly increase the biomethanol production cost by about 45 %. In these cases, the optimal production cost of biomethanol varies from 841 \$ t^{-1} to 939 \$ t^{-1}.

At this cost, biomethanol can compete easily with lignocellulosic ethanol which has a minimum selling price in the range of 1139 \$ t^{-1} and 1202 \$ t^{-1} [153]. However, it is evident that, at this time, lignocellulosic ethanol and biomethanol cannot compete with corn and sugarcane ethanol as their minimum selling price is very low (380 \$ t^{-1} to 506 \$ t^{-1}) [153]. Nonetheless by considering financial incentives offered by the government to transform the forest industry and to develop new products in the forest sector [145], the biomethanol production cost could be reduced. Biomethanol could then be a promising option that can compete with conventional as well as lignocellulosic ethanol.

The results of this study can help government decision makers for renewable fuel planning purposes and PM owners to evaluate cost-effective scenarios to convert PM into integrated biorefineries for biomethanol synthesis. Moreover, the evaluation of the different scenarios underlines that the operational constraints affect significantly the design of biomass supply chains in terms of location and number of eligible integrated biorefineries and their potential capacities.

Future research could include a similar model tested in the whole country or applied for F-T diesel production to attain the renewable diesel production target.

However, one of the most important limitations of the model parameters is that zero inventories and inventory carry-over are assumed for both biomass and biofuel products. Considering inventory could affect the optimal biomethanol cost. In addition, with the improvement of the syngas conversion process, the efficiency of the biomethanol production process can be enhanced considerably, which can significantly affect the model results. The model does not account also for risks of uncertainty in resource supply which can influence the stability and the profitability of supply chains [141]. Therefore, this study represents an optimistic assessment of biomethanol potential production from logging residues, fire-damaged stand and sawmill residues.

6.6 Conclusions

This study focused on the design of the integrated biorefinery supply chain in order to satisfy the Eastern Canada biomethanol demand in an optimal price. It showed that up to 10 % biomethanol in gasoline could be provided in Eastern Canada from forest biomass. This study, along with other works [82, 123, 126, 154] intends to develop a biofuels industry in Canada based on the federal and provincial renewable fuel regulations. Industrial growth of biofuels requires safe, stable and sustainable feedstocks therefore optimizing the supply chain of both forest biomass and agricultural residues could ensure the sustainable development of biofuels.

6.7 Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

6.8 Acknowledgements

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6.9 Supplementary materials

Table A.1: list of sets, parameters and variables used in the optimization model

Sets	
b	Set of FB sources
p	Set of capacity level
i	Set of FB procurement sites
j	Set of sawmills
k	Set of PM sites
l	Set of petroleum refineries sites
Parameters	
Eff	Conversion efficiency of the biomethanol process (t odt^{-1})
$Rc_{b,i}$	Recovery rate of FB 'b' in procurement site 'i' (%)
$Bq_{b,i}$	Available amount of FB 'b' in procurement site 'i' (odt y^{-1})
Sq_j	Available amount of SR in sawmill 'j'(odt y^{-1})
Rsr	Average percentage of SR that can be shared (%)
Msr	Minimum amount of SR that should be recovered (%)
Lo_p	Lower bound of the FBR capacity with the capacity level 'p' (t y^{-1})
Up_p	Upper bound of the FBR capacity with the capacity level 'p' (t y^{-1})
Mp	Minimum production amount as a percentage of the integrated biorefinery capacity (%)
Mcap	Minimum capacity of the integrated biorefinery (t y^{-1})
$Demm_l$	Annual biomethanol demand (t y^{-1})
$Cb_{b,i}$	Harvesting cost of FB 'b' supplied from procurement site 'i' ($ odt^{-1})
Csr	Purchased cost of SR ($ odt^{-1})
Fcp	Fixed production cost of biomethanol ($ t^{-1})
Vcp	Variable production cost of biomethanol ($ t^{-1})
Ic_p	Investment cost of installing an integrated biorefinery with capacity level 'p' ($)
IR	Interest rate (%)
te	Economical lifetime (y)
$Fbtc_b$	Fixed transportation cost of FB 'b' ($ odt^{-1})
$Vbtc_b$	Variable transportation cost of FB 'b' ($ odt^{-1})
Fstc	Fixed transportation cost of SR ($ odt^{-1})
Vstc	Variable transportation cost of SR ($ odt^{-1})
Parameters	

Fmtc	Fixed transportation cost of biomethanol ($ t^{-1})
Vmtc	Variable transportation cost of biomethanol ($ t^{-1})
$Dbr_{i,k}$	Distance between FB procurement site 'i' and PM 'j' (km)
$Dsr_{j,k}$	Distance between SW 'j' and PM 'k'(km)
$Drd_{k,l}$	Distance between FBR located in 'k' and petroleum refinery 'l' (km)
Nga_k	Quantity of natural gas avoided in FBR located in 'k' (t y^{-1})
Ngc	Natural gas purchased cost ($ t^{-1})
Variables	
$Yb_{b,i,k}$	1 if FB 'b' is transported from the procurement site 'i' to the FBR located in 'k'
$Ys_{j,k}$	1 if SR is transported from the SW 'j' to the FBR located in 'k'
$Yc_{k,p}$	1 if the capacity level 'p' is chosen for the FBR located in 'k'
$Sfb_{b,i,k}$	Total quantity of FB supplied from site 'i' to the FBR located in 'k' (t y^{-1})
$Ssr_{j,k}$	Total quantity of SR supplied from SW 'j' to the FBR located in 'k' (t y^{-1})
cap_k	Annual production capacity of the FBR located in 'k' (t y^{-1})
$capr_{p,k}$	Annual production capacity of the FBR located in 'k' with capacity level 'p' (t y^{-1})
Pm_k	Total biomethanol produced in an integrated biorefinery located in 'k' (t y^{-1})
$Tm_{k,l}$	Total biomethanol quantity transported from 'k' to 'l' (t y^{-1})
Tac	Total annual cost ($ y^{-1})
Aic	Total annualized investment cost ($ y^{-1})
Bpc	Total biomass procurement cost ($ y^{-1})
Btc	Total biomass transportation cost ($ y^{-1})
Mpc	Total biomethanol production cost ($ y^{-1})
Mtc	Total biomethanol transportation cost ($ y^{-1})
Ngp	Total profit from natural gas substitution ($ y^{-1})

Table A.2: Making processes and capacities of the considered pulp mills

Pulp mills (Province)	**Process**	**Capacity (t y^{-1})**
PM1 (ON)	Kraft process -dissolving pulp mill	310000
PM2 (ON)	Kraft process	328000
PM3 (ON)	Kraft process	335000
PM4 (ON)	Kraft process	564000
PM5 (QC)	Kraft process	447000
PM6 (QC)	Kraft process	90000
PM7 (QC)	Kraft process	356000
PM8 (QC)	Kraft process	58000
PM9 (QC)	High yield Pulp process	315000
PM10 (QC)	Thermo mechanical process	240000
PM11 (QC)	Kraft process	505000
PM12 (QC)	Kraft process-dissolving pulp mill	200000
PM13 (QC)	Thermo mechanical process	200000
PM14 (NB)	Kraft process-dissolving pulp mill	127000
PM15 (NB)	Kraft process-dissolving pulp mill	173000
PM16 (NB)	Kraft process	420000
PM17 (NB)	Chemical and mechanical processes	370000
PM18 (NL)	Thermo mechanical process	250000

Table A.3: Biomethanol demand in Eastern Canadian petroleum refineries considering 5 % blended gasoline

Eastern Canadian petroleum Refineries (province)	**Biomethanol demand (Mt y^{-1})**
Id 1 (NB)	1.92
Id 2 (QC)	1.60
Id 3 (QC)	0.83
Id 4 (ON)	0.27
Id 5 (ON)	0.41
Id 6 (ON)	0.44
Id 7 (ON)	0.31
Id 8 (NL)	0.69
Total demand	**6.46**

Table A.4: Quantities of fire-damaged stands and logging residues available in a radius of 100 and 150 km from the considered pulp mills (Mt y^{-1})

Pulp mills (province)	**fire-damaged stand availability**		**Logging residues availability**	
	100 km	**150 km**	**100 km**	**150 km**
PM1 (ON)	1.227	1.631	0.972	2.474
PM 2 (ON)	1.133	1.510	2.350	4.921
PM 3 (ON)	0.0398	0.140	0.740	2.106
PM 4 (ON)	0.198	0.759	1.558	2.370
PM 5 (QC)	0.0146	0.040	0.427	0.897
PM 6 (QC)	0.0278	0.0499	0.914	2.362
PM 7 (QC)	4.535	8.899	2.269	4.740
PM 8 (QC)	0.0381	0.0143	0.713	0.666
PM 9 (QC)	0.0 535	0.110	1.397	2.526
PM 10 (QC)	0.0200	0.0254	0.349	0.713
PM 11 (QC)	0.01167	0.114	0.0669	3.106
PM 12 (QC)	0.00068	0.000778	0.0188	0.0142
PM 13 (QC)	0.0003	0.0112	0.0044	0.0147
PM 14 (NB)	0.0178	0.0316	3.171	4.558
PM 15 (NB)	0.0255	0.0340	3.534	4.122
PM 16 (NB)	0.000026	0.000028	0.0093	0.0054
PM 17 (NB)	0.0055	0.0401	1.042	6.245
PM 18 (NL)	0.019	0.0 449	1.006	0.579
Total	7.31	13.41	20.54	42.42

Table A.5: Feedstock and biomethanol related parameters

Parameters (Units)	**Value**	**Sources**
Volume capacity of biomass truck (m^3)	70	[84]
Payload of biomass truck (t)	22.7	[84]
Rate of payment for biomass ($\$ h^{-1}$)	85	[131]
Average speed of biomass truck ($km\ h^{-1}$)	80	Assumption
Fixed time for loading, unloading and delay per trip (h)	2.5	[131]

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CHAPITRE 7 ARTICLE 4: MULTICRITERIA OPTIMIZATION FOR THE DESIGN OF AN INTEGRATED FOREST BIOREFINERY SUPPLY CHAIN IN CANADA

Renewable Resources and Biorefineries

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7.1 Abstract

Integrated forest biorefineries supply chains are relatively new and the interaction between their different components is complex. This study proposes a multicriteria optimization model to assess the trade-offs between the economic and environmental performances of the supply chain. The defined model accounts for different forest biomass types, feedstocks availabilities, forest biomass harvesting seasonality, stored biomass degradation, petroleum refineries demand, government funds as well as carbon pricing program. It determines the feedstock choice as well as the capacities and locations of the integrated forest biorefineries. The multicriteria optimization program developed is solved with an Epsilon-constraint approach. The proposed model has been applied in the case of the production of biomethanol and F-T diesel in Eastern and Western Canada to fulfil different gasoline and diesel blending requirements, respectively.

The results indicate that Eastern and Western Canada could be self-sufficient in the production of biomethanol as a fuel additive in gasoline up to 10% (corresponding to a production level of 13 Mt y^{-1} and 5 Mt y^{-1} in Eastern and Western Canada respectively). The results show that Western Canada has a potential to produce up to 3.7 Mt y^{-1} of F-T diesel which can meet the demand for about 4 % blending with diesel. Moreover, the results reveal how the biofuels production costs as well as the locations of the integrated forest biorefineries change by increasing the demand level and by considering operational constraint and environmental performances of the supply chain.

7.2 Highlights

- A multicriteria optimization model for the integrated forest biorefinery supply chain design is developed.
- The greenhouse gas emissions, fossil resources consumption and total costs of biofuels production are minimized.
- Dead wood stems and harvesting residues are investigated as potential forest biomass sources for biofuels synthesis.
- The production of biomethanol-gasoline blends and F-T diesel-diesel blends are compared in Eastern and Western Canada.

7.3 Introduction

The global wood-based bioenergy market is growing driven by the policy imperatives of mitigating greenhouse gas (GHG) emissions and improving energy security. Bioenergy currently provides about 10 % of global primary energy supply, accounting for roughly 80 % of the energy derived from renewable sources. However, the socioeconomic and environmental benefits of replacing fossil fuels with bioenergy are complex, and debates are ongoing on issues such as environmental sustainability of biomass production and procurement, and performance of supply chains. To respond to these concerns and to increase its role within the renewable energy transition, Canada's forest sector is considering strategies to expand the sustainable mobilization of forest biomass supply chains.

Supported by more than 230 million hectares of managed forest, the wood-based bioeconomy in Canada is emerging (1). Forests are a major source of wealth for Canadians, providing a wide range of economic, social and environmental benefits. In 2016, production in the forest sector contributed $21 billion—or 1.25 %—to Canada's real gross domestic product (2). Canada has the most biomass per capita in the world and represents 6.5 % of the world's theoretical bioenergy potential (3, 4). Building on its large forest sector, the development of integrated forest biorefineries (IFBR) in Canada, seems a promising avenue to mitigate the GHG emissions and play an increasing role in the future of global bioenergy and the emerging bioeconomy (5).

The integration of the forest biorefineries to an operating pulp and paper mills (PM) could maximize the value of the supply chain as its performance depends strongly on the costs, consistency and efficiency of the forest biomass supply (6). Moreover, forest-based biofuels generated in the IFBR can substitute the fossil fuel used internally in the PM, thus making the entire complex a fossil fuel free facility (7). Existing PM are ideal sites for IFBR for various reasons. They have well established networks for biomass harvesting, transporting and processing. PM can act as collection points to provide forest biomass for biorefining activities in an optimal way (8, 9). In terms of proximity to markets and feedstocks, PM are located near numerous sources of biomass, such as forest and agricultural residuals, and energy crops, and have existing infrastructure to ship finished product. They are also located close to roads and rail connectors which allow the IFBR to easily deliver biofuels to market (10). Moreover, PM have a highly trained workforce able to operate energy and biorefinery systems. On the other hand, IBFR represents an emerging opportunity that will expand the revenues and maintain the viability of the PM by diversifying their products portfolio (7, 11, 12).

In Scandinavian countries and especially in Finland and Sweden, biorefining has become a major focus of attention for the pulp and paper industry as the forest has always been an important resource for local use and for the export of products. The IFBR pathways will vary depending on the pulping technology used. At least four main pathways could be cited: 1) Transformation of the pulp fibres into new products (cellulose fibres, nanocellulose, etc) 2) recovering of residue streams to marketable products (lignin, hemicellulose, etc.) 3) Pre-processing of incoming raw material to produce fuels or chemicals (extraction of hemicellulose

for fermentation to ethanol or for use as chemicals, etc.). 4) Recovering of logging residues and other forest biomass with limited use which co-produce steam and marketable products (gasification of forest residues to produce motor fuel and steam, pyrolysis of forest residues to produce pyrolysis oil, char and steam, etc).

However, one of the barriers to the biorefinery diffusion is the bioenergy value chain. In fact, the socioeconomic and environmental benefits of competing traditional fossil fuels supply chains with IFBR are complex. Debates are ongoing on issues such as environmental sustainability of biomass production and procurement, and competitiveness of supply chains. The design of a sustainable and competitive wood-based bioenergy supply chain is therefore crucial to accommodate these aforesaid challenges.

This study is based on a previous analysis done by B. Cheikh et al. (13) optimizing the design of the IFBR supply chain including, an economic perspective, feedstock choice and allocation, IFBR locations and capacities from.

The objectives of this work are to: 1) design the IFBR supply chain under defined economic and environmental criteria, 2) compare the supply chains of biomethanol and F-T diesel synthesis in Eastern and Western Canada in terms of production cost, choice of the forest biomass resources as well as locations and capacities of the IFBR, and 4) identify the parameters affecting the design of the IFBR supply chains among operational constraint of biomass and biofuels demands. To meet these objectives, a multicriteria optimization model has been developed. It enables the generation of supply chain alternatives leading to significant environmental and economic benefits.

7.4 Material and methods

7.4.1 Study area and industrial network

Using the industrial network of Eastern and Western Canada, the design of the IFBR supply chain is proposed for two case studies. One for the production of biomethanol and another one for the F-T diesel.

The quantity of LR and DW available within a radius of 150 km from PM in Canada was estimated by using the approach proposed by Mansuy et al. (5) and described in the work of B. Cheikh et al. (13).

In eastern Canada, consisting of the provinces of Ontario, Quebec and New Brunswick, 18 PM are chosen. Approximately 55 Mt of forest resources are produced in 2010 within a radius of 150 km from PM including 13 Mt $^{-1}$ of DW and 42 $^{-1}$ Mt of LR. The biofuels synthesis in the Eastern Canada could be delivered to 8 petroleum refineries actually producing fossil transportation fuels (14) (Fig. 7-1). Based on a blending requirement of 5% for biomethanol and 2 % for F-T diesel, the petroleum refineries could produce 6.5 Mt y^{-1} and 2.6 Mt y^{-1} of biomethanol and F-T diesel respectively (The refining capacities of the eastern petroleum refineries are presented in Table A-1 in the appendix.)

In western Canada, which include the provinces of British Columbia, Alberta and Saskatchewan, 17 PM are selected as potential sites for biorefining activities Compared to the eastern provinces, a higher concentration of forest resources estimated at 55 Mt $y^{-1}$of DW and 79 Mt $y^{-1}$of LR is available within a radius of 150 km from the PM (Fig. 7-1). Western Canada contains six petroleum refineries that could produce 1.84 Mt of F-T diesel and 2.3 MT of biomethanol annually to supply 5% of the current gasoline usage and 2 % of the fossil diesel usage, respectively.

Neither biomethanol nor F-T diesel based biorefineries have yet been constructed at commercial scale based on the thermochemical platform and it is difficult to predict their capacities. It has been determined that the most attractive size of a biorefinery producing biofuels would be comprised between 0.76 and 1.53 Mt y^{-1} (15) in order to be economically viable. In this study, the minimum capacity was fixed at 0.35 Mt y^{-1} for IFBR producing F-T diesel and 0.95 Mt y^{-1} for those generating biomethanol. The limitations in minimum plant size are caused by the biomass availabilities around PM and the process efficiencies.

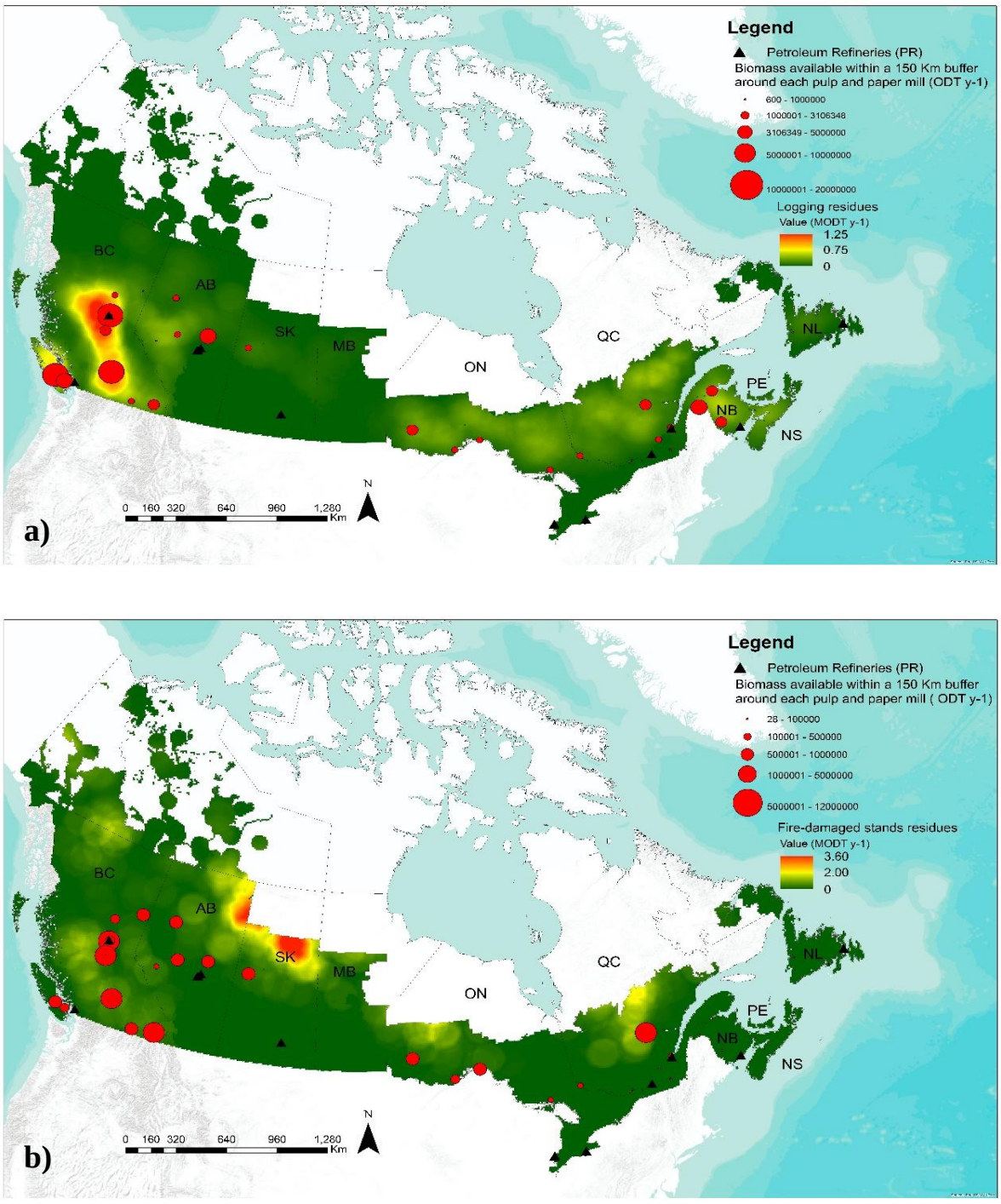


Figure 7-1: The quantity of biomass available within a radius of 150 km around each pulp and paper mill a) from logging residues, b) from fire-damaged stands

7.4.2 **Methodology**

In this study, two scenarios have been evaluated according to the biofuels demands. The IFBR supply chain is firstly studied when the biomethanol and F-T diesel are used to supply 5% of the current gasoline usage and 2 % of the fossil diesel usage, respectively, based on the existing Canadian renewable fuels regulations (scenario 1). Only the economic objective is considered for this case. In scenario 2, a doubled biofuel blending requirement has been assumed. This scenario takes into account both the economic and environmental objectives presented in terms of GHG emissions and fossil fuel consumptions.

The methodology used in this study is similar to the one developed by B. Cheikh et al. (13). Both of the proposed models address all the stages of the biofuels life cycle including biomass harvesting and treatment, feedstock transportation as well as biofuel synthesis and distribution. Moreover, the two developed models take into account different types of biomass, geographical availability of feedstock as well as petroleum refineries demands and locations. However, the novelties considered in the analysis are described below:

– Environmental performance consideration

The current study is distinguished by the consideration of the environmental performance as an additional criterion in the optimal design of the IFBR supply chain. The environmental performance is evaluated with respect to GHG emissions and fossil resources consumption based on life cycle analysis approach developed by B. Cheikh et al. (16). To consider the economic and environmental performances of the supply chain, an integrated approach is developed in this study using the outcomes data from the life cycle analysis as inputs into the multicriteria optimization model. The Epsilon–constraint method was used to solve the trade-offs between the economic and the environmental objectives(17-19). This method allows identifying a set of optimal compromise solutions lie on a specific curve called 'Pareto curve' revealing trade-offs between the two objectives. When moving from one point on the Pareto curve to another, one objective function improves while the other worsens. All the solutions above this Pareto curve are suboptimal solutions that can be improved and any solution below this curve is infeasible (20).

– Harvesting seasonality

Harvesting seasonality is taken into account since the harvesting activities are constrained by weather conditions and type of soil in Canada. In fact, on sites without special constraints (fairly thick, normally drained soil), wood harvesting can be done all year round, except during periods of high humidity which are in spring and autumn. On the other hand, harvesting on wet soils (peaty soils) or fragile soils (thin soils) is usually done in winter to take advantage of the frozen ground and snow cover. Thus, 12-time periods per year are considered to address the seasonality of forest biomass feedstocks (forest biomass is not harvested in March and April and from early September to the end of november). Feedstock and biofuels storage steps are then added in the biofuels life cycle. Biomass degradation rate is therefore considered in this work to model the degradation characteristic of biomass feedstock.

– Economic benefit of avoiding fossil fuels

Fossil fuels avoided from the implementation of the IFBR are assumed to have an economic benefit based on the carbon pricing program to be established by the federal government (10 $ per tonne of CO_{2e}) (21). Furthermore, government funds related to the development of Canadian clean technology projects have been considered.

7.4.3 **Data acquisition**

Data related to feedstock availabilities, characteristics and costs are presented in the work of B.Cheikh et al. (13) and are therefore not detailed in this study. Procurement costs of LR and DW as well as salvage harvesting cost of dead trees in Eastern and Western Canada are obtained from studies (22-26). Due to the harvesting seasonality, the forest biomass is stored to satisfy the biomass demand throughout the year. The unit storage cost of forest biomass is estimated at 1.53 $\$ t^{-1} d^{-1}$ (27). Biomass loss due to storage step is assumed at 0.29% and 2.2% per month for DW and LR respectively based on the work of Wihersaari et al. (28). The maximum storage time is fixed at one month in this study.

In the work of B.Cheikh et al. (13), the data related to biofuels production and transportation costs was presented as examples for biomethanol synthesis. In the present study, the process

configurations and costs considered for the selected biofuels are adapted respectively from the National Renewable Energy Laboratory (29) and the US Department of Energy (30). F-T diesel and biomethanol purchased equipment costs are presented in Table A.2 in the appendix. Biofuels storage costs are estimated at 3.56 \$ t^{-1} and 5.33 \$ t^{-1} respectively for biomethanol and F-T diesel (31). Costs data related to biofuels transportation are obtained from B. Cheikh et al. (13). Credits from selling by-products and from substituting natural gas by syngas (used to fire the lime kiln and to initiate the bark boiler operation) are considered in this study. The purchased cost of natural gas avoided is assumed to be 2.85 (\$ GJ^{-1}). Electricity is send to the grid with a selling price of 0.73 (\$ KWh^{-1}) (32). Gasoline selling price is estimated at 131 \$ t^{-1} (33). Furthermore, government funds related to the development of Canadian clean technology projects have been considered. We assume that the maximum allowable funding amount is around 15M \$ and should not exceed 33% of the total capital investment cost (34).

Data related to GHG emissions and the fossil resources consumption for the supply chain steps, except for the feedstocks and biofuels storage steps are obtained from the work of B. Cheikh et al. (16). In this study, Life Cycle Analysis approach has been used to quantify and compare the environmental performances related to the synthesis of biomethanol and Fischer-Tropsch diesel in a Canadian context using the SimaPro Software. The GHG emissions data related to biomass storage are estimated at 339 kg CO_{2e} odt^{-1}, 383 kg CO_{2e} $odt^{-1}$and 664 kg CO_{2e} odt^{-1} for LR, bundles and DW, respectively, based on the work of Jäppinen (35). The biofuels storage emissions data are estimated at 26 kg CO_{2e} $t^{-1}$and 55 kg CO_{2e} t^{-1} for biomethanol and F-T diesel respectively (36).

7.4.4 Formulation of the multicriteria optimization model

For the problem addressed in this work, a multicriteria optimization model has been developed. The mathematical model is defined by a number of operational and technical constraints (Eq. (1) to Eq. (18)), and objective functions to optimize. The economic objective is defined in Eq. (19) to Eq. (29). The objective of reducing the GHG emissions is defined in Eq. (30) to Eq. (39) and the objective of minimizing the fossil resources consumption is presented in

Eq. (40) to Eq. (47). The list of sets, parameters, and variables is given in Table A.3 in the appendix.

7.4.4.1 **Model Constraints**

According to Eq. (1), the total quantity of biomass harvested is constrained by the available amount, the corresponding recovery rate and the seasonal availability of feedstock.

$$Hb_{b,i,t} \leq Wf_{i,t} \,.\, Rr_{b,i,t} \,.\, Bq_{b,i,t} \quad \textbf{(1)}$$

Where $'Hb_{b,i,t}'$ is the total biomass quantity of biomass 'b' supplied from procurement site 'i' at time period 't', $'Bq_{b,i}'$ is the available amount of biomass 'b' in 'i' at time period 't'. The seasonal availability of feedstock is taken into account throw the parameter $'Wf_{i,t}'$ and the operational constraints throw the recovery rate parameter $'Rr_{b,i,t}'$ of the biomass 'b' in procurement site 'i'.

The quantity of biomass 'b' harvested from site 'i' should be equal to the total amount of biomass shipped to the IFBR 'j' at the time period 't'. We assumed that the procurement sites do not store feedstocks.

$$Hb_{b,i,t} = \sum_j Tb_{b,i,j,t} \quad \textbf{(2)}$$

Where $'Tb_{b,i,j,t}'$ is the biomass type 'b' shipped from procurement site 'i' to the IFBR installed in 'j' at time period 't'.

The biomass can be transported from 'i' to 'j' at period time 't' only if the biomass is selected to be supplied from 'i' and used in the IFBR installed in 'j'.

$$Tb_{b,i,j,t} \leq M \,.\, Yb_{b,i,j,t} \quad \textbf{(3)}$$

Where M is a big number.

The total forest biomass 'b' shipped from all the procurement facilities 'i' to the IFBR installed in 'j' at time period 't' plus the biomass stored available at the plant $'Sb_{b,j,t-1}'$ at the time period 't-1'should be equal to the biomass used $'Ub_{b,j,t}'$ for the current time period 't' and the quantity that will be stored at the end of the time period 't', $'Sb_{b,j,t}'$.

$$\sum_i Tb_{b,i,j,t} + \left(1 - Db_{b,t}\right) .\; Sb_{b,j,t-1} = Ub_{b,j,t} + Sb_{b,j,t} \quad \textbf{(4)}$$

The biomass deteriorated during the storage period is considered through the parameter $Db_{b,t}$ which is the deterioration rate of the biomass 'b' at the time period 't'.

The mass balance relationship of biofuel in the IFBR 'j' at time 't' is given by Eq. (5)

$$Pf_{j,t} + Sf_{j,t-1} = \sum_k Tf_{j,k,t} + Sf_{j,t} \quad \textbf{(5)}$$

Where $'Pf_{j,t}'$ is the quantity of biofuel produced at the IFBR installed in 'j' at time 't', $'Sf_{j,t-1}'$ is the biofuel stored at the end of the previous period time, $'Tf_{j,k,t}'$ is the amout of biofuel transported to demand center 'k' and $'Sf'_{j,t}$ is the inventory level at the end of the period time 't'.

To model the selection of one capacity level 'l', a binary variable $'Yc_{j,l}'$ has been added; maximum one capacity level can be chosen if an IFBR is installed in 'j'.

$$\sum_l Yc_{j,l} \leq 1 \quad \textbf{(6)}$$

To consider only one biomass type and form, Eq. (7) is added.

$$\sum_{b,i,t} Yb_{b,i,j,t} = \sum_l Yc_{j,l} \quad \textbf{(7)}$$

The capacity of the IFBR installed in 'j' with the capacity level 'l' is limited by the lower, $'Lo_L'$, and the upper, $'Up_L'$,capacities of the same capacity level 'l'.

$$Lo_l \times Yc_{j,l} \leq Capl_{j,l} \leq Up_l \times Yc_{j,l} \quad \textbf{(8)}$$

The annual production of the IFBR 'j', $'Cap_j'$, is the sum of the elementary capacities $'Capl_{j,l}'$.

$$Cap_j = \sum_l Capl_{j,l} \quad \textbf{(9)}$$

The total biofuel produced in the IFBR installed in 'j', $'Pf_{j,t}'$, is related to the total amount of biomass consumed , $'Ub_{b,i,t}'$, by the conversion factor of the process plant $'Ef_b'$. In this work, we assumed that the conversion factors of the process plant are not affected by the capacity of the IFBR.

$$Pf_{j,t} = \sum_b Ef_b \,.\, Ub_{b,j,t} \quad \textbf{(10)}$$

The total biofuel produced in the IFBR installed in 'j' should be comprised between the capacity of the IFBR and the capacity utilization rate.

$$Mp\,.\,(Dp_t\,/Pa)\;.\;Cap_j \le Pf_{j,t} \le (Dp_t\,/Pa)\,.\;Cap_j \qquad \textbf{(11)}$$

Where Mp is the minimum production amount as a percentage of capacity for the IFBR, $'Dp_t\,'$, is the duration of the time period and $'Pa\,'$ is the production time duration of a year.

The total quantity of by-product 'q' synthesis in the IFBR installed in 'j' at time period 't' , is related to the total amount of biomass consumed $'Ub_{b,j,t}'$, by the conversion factor of biofuel to by-product $'Bpef_q'$.

$$Pbp_{j,q,t} = \sum_b Bpef_q\,.\;Ub_{b,j,t} \qquad \textbf{(12)}$$

The total biofuel shipped from all the IFBR installed in 'j', $'Tf_{j,k,t}'$,to the demand center 'k' should be greater than the demand $'Df_{k,t}'$ in time period 't'.

$$\textstyle\sum_j Tf_{j,k,t} \ge Df_{k,t} \qquad \textbf{(14)}$$

The government incentive, $'Ginc_j'$, is limited by the constraints defined in Eq. (14) and Eq. (15).

$$Ginc_j \le Gimax\,.\;\textstyle\sum_l Yc_{j,l}$$
$$Ginc_j \le Giper\,.\,Tic_j \qquad \textbf{(15)}$$

Where $'Gimax'$ is the maximum allowable incentive amount and $'Giper'$ is the percentage of the total capital cost.

The capacity of the IFBR 'j', $'cap_j\,'$, should be greater than the minimum plant capacity 'Mcap'.

$$cap_j \ge\; Mcap\,.\,Yc_{j,l} \qquad \textbf{(16)}$$

To model the procurement of forest biomass within a fixed radius from each PM, constraints 17 and 18 added. They force the supply chain configuration to choose forest biomass from only their radius.

(17)

$$Yb_{b,i,j,t} \geq diag_{i,j} \ .\ (1\text{-}\ diag_{i,j})$$

$$Yb_{b,i,j,t} \leq diag_{i,j} \quad \textbf{(18)}$$

7.4.4.2 **Economic objective: maximizing the total annual profits**

The economic objective is to minimize the total annual costs $'Tc'$, including the total production costs, total transportation costs, total annualized capitals, the annual operation costs, total storage costs and total profits from natural gas saving and by-products selling.

$$Tc = \sum_j Tac_j + Tbpc_j + Tbtc_j + Tbsc_j + Tcc_j + Tfsc_j + Tftc_j - Tbyc_j - Tngc_j \quad \textbf{(19)}$$

The investment capital cost of the IFBR installed in 'j' is calculated using an interpolated piecewise linear cost curve for each capacity level 'l'.

$$Tic_j = \sum_l (Ic_{l-1} \ .\ Yc_{j,l}) + ((Capl_{j,l} - Lo_l \,.\, Yc_{j,l}) \,.\, (\tfrac{Ic_l - Ic_{l-1}}{Up_l - Lo_l})) \quad \textbf{(20)}$$

where $'Ic_l'$ is the investment cost of installing the IFBR 'j' with capacity level 'l', $'Up_l'$ and $'Lo_l'$ is the upper and lower bounds of the IFBR capacity with capacity level l. We note that $'Tic_j'$ equals zero if $'Yc_{j,l}'$ is nil.

The total annualized capital cost is given by Eq. (21).

$$Tac_j = \frac{IR}{1 - \frac{1}{(1+IR)^{El}}} \ .\ (Tic_j - Ginc_j) \quad \textbf{(21)}$$

Where $'IR\,'$ is the interest rate and $'El\,'$ is the economical lifetime.

The total biomass procurement cost $'Tbpc_j'$ is given by Eq. (22).

$$Tbpc_j = \sum_{b,t,i} Cb_{b,i} \ .\ Tb_{b,i,j,t} \quad \textbf{(22)}$$

$'Cb_{b,i}'$ is the harvesting cost of biomass 'b' supplied from procurement site 'i'

The total biomass transportation cost presented by Eq. (23) takes into account both distance variable costs and distance fixed costs.

$$Tbtc_j = \sum_{b,i,t} \left(Fbtc_b + Vbtc_b \,.\, Dbr_{i,j}\right) . Tb_{b,i,j,t} \quad \textbf{(23)}$$

The total biomass and biofuels storage costs are defined in Eq. (24) and Eq. (25).

$$Tbsc_j = \sum_t Sbc_{b,j} \,.\, Dp_t \;.\; Sb_{b,j,t} \quad \textbf{(24)}$$

$$Tfsc_j = \sum_t Sfc_j \;.\; Sf_{j,t} \quad \textbf{(25)}$$

The total conversion cost of the IFBR installed in 'j' is the sum of fixed cost,Fcc, dependent only on the capacity of the IFBR $'Cap_j'$ and variable cost $'Vcc'$ expressed in terms of biofuel output $'Pf_{j,t}'$.

$$Tcc_j = \sum_t Vcc \,.\, Pf_{j,t} + \; Fcc \,.\, Cap_j \quad \textbf{(26)}$$

In our study, we suppose that fixed and variable conversion costs are independent of the type of biomass used.

The total biofuels transportation cost is given by Eq. (27).

$$Tftc_j = \sum_{k,t} \left(Fftc + Vftc.\; Drd_{j,k}\right) . Tf_{j,k,t} \quad \textbf{(27)}$$

Where $'Fftc\,'$ is the fixed transportation cost and $'Vftc'$ is the variable transportation cost.

The total by-product credit

$$Tbyc_j = \sum_{q,t} Pbc_q \,.\, Pbp_{j,q,t} \quad \textbf{(28)}$$

The total natural gas credit

$$Tngc_j = Png \;.\; Ngu_j \,.\, Yc_{j,l} \quad \textbf{(29)}$$

Where $'Ngu_j'$ is the quantity of natural gas used in PM 'j' and $'Png'$ is the unit purchasing cost of natural cost.

7.4.4.3 **Environmental objective: Minimizing the GHG emissions**

The environmental objective is to minimize the total annual GHG emissions $'Te\,'$ resulting from the operations of the biofuel supply chains. The objective function is defined in Eq. (30).

$$Te = \sum_j Tbpe_j + Tbte_j + Tbse_j + Tfpe_j + Tfse_j + Tfte_j - Tbye_j - Tnge_j - Tfae_j \quad \textbf{(30)}$$

Where

$'Tbpe_j'$ is the total GHG emissions of procuring biomass:

$$Tbpe_j = \sum_{b,t} Eb_{b,i} \ . \ Ub_{b,j,t} \quad \textbf{(31)}$$

$'Tbte_j'$ is the total GHG emissions of transporting biomass:

$$Tbte_j = \sum_{b,i,t} Etb_b \ . Dbr_{i,j} \ . Tb_{b,i,j,t} \quad \textbf{(32)}$$

$'Tbse_j'$ is total GHG emissions of storing biomass:

$$Tbse_j = \sum_{b,t} Esb_b \ . Dp_t \ . \ Sb_{b,j,t} \quad \textbf{(33)}$$

$'Tfpe_j'$ is total GHG emissions of producing biofuel:

$$Tfpe_j = \sum_t Epf \ . Pf_{j,t} \quad \textbf{(34)}$$

$'Tfse_j'$ is the total GHG emissions of storing biofuel:

$$Tfse_j = \sum_t Esf \ . \ Sf_{j,t} \quad \textbf{(35)}$$

$'Tfte_j'$ is the total GHG emissions of transporting biofuels from the IFBR to the petroleum refinery:

$$Tfte_j = \sum_{k,t} Etf \ . Drb_{j,k} \ . Tf_{j,k,t} \quad \textbf{(36)}$$

$'Tbye_j'$ is the total GHG emissions credit from producing unit quantity of by-product q:

$$Tbye_j = \sum_{q,t} Ebp_q \ . \ Pbp_{j,q,t} \quad \textbf{(37)}$$

$'Tnge_j'$ is the total GHG emissions credit from natural gas substitution:

$$Tnge_j = Eng\ .\ Ngu_j \quad \textbf{(38)}$$

$'Tfae_j'$ is the total GHG emissions credit from fossil fuel substitution:

$$Tfae_j = \sum_t Eaf\ .\ Pf_{j,t} \quad \textbf{(39)}$$

7.4.4.4 **Environmental objective: Minimizing the fossil resources consumption**

$$Tr = \sum_j Tbpr_j + Tbtr_j + Tfpr_j + Tftr_j - Tbyr_j - Tngr_j - Tfar_j \quad \textbf{(40)}$$

Where $'Tbpr_j'$ is the total fossil resources consumption of procuring biomass:

$$Tbpr_j = \sum_{b,t} Rpb_{b,i}\ .\ Ub_{b,j,t} \quad \textbf{(41)}$$

$'Tbtr_j'$ is the total fossil resources consumption of transporting biomass:

$$Tbtr_j = \sum_{b,i,t} Rtb_b\ .\ Dbr_{i,j}\ .Tb_{b,i,j,t} \quad \textbf{(42)}$$

$'Tfpr_j'$ is total fossil resources consumption of producing biofuel:

$$Tfpr_j = \sum_t Rpf\ .Pf_{j,t} \quad \textbf{(43)}$$

$'Tftr_j'$ is the total fossil resources consumption of distributing biofuels from the IFBR to the petroleum refinery:

$$Tftr_j = \sum_{k,t} Rtf\ .\ Drb_{j,k}\ .\ Tf_{j,k,t} \quad \textbf{(44)}$$

$'Tbyr_j'$ is the fossil resources avoided from producing unit quantity of by product q:

$$Tbyr_j = \sum_{q,t} Rbp_q\ .\ Pbp_{j,q,t} \quad \textbf{(45)}$$

$'Tngr_j'$ is the fossil resources avoided from substituting natural gas by syngas:

$$Tngr_j = Rng.Ngu_j \quad \textbf{(46)}$$

$'Tfar_j'$ is the fossil resources credit from fossil fuel substitution:

$$Tfar_j = \sum_t Raf \ . Pf_{j,t} \quad \textbf{(47)}$$

7.5 Results

7.5.1 Case study 1: Methanol synthesis

7.5.1.1 Scenario1: Economic optimization of the biomethanol supply chain

For the synthesis of biomethanol in Eastern Canada, four IFBR located in Ontario (PE2), Quebec (PE7 and PE11) and New Brunswick (PE14) are identified (Table 7-2). The production capacity varies between 1.17 Mt y^{-1} to 1.85 Mt y^{-1}, which is limited by the biomass availability, and the distances between the PM and the PR. Overall, 80 % of the biomethanol production in Eastern Canada is satisfied by IBFR located in Quebec and Ontario (49 % and 31 % respectively) whereas the remaining is produced in New Brunswick. This scenario uses 100 % of LR as the IFBR are integrated into PM with abundant resources of LR.

On the other hand, for the synthesis of biomethanol in Western Canada, two IFBR located in British Columbia (PW13) and Saskatchewan (PW17) are identified which have a production capacity of 1.15 Mt y^{-1} and 1.12 Mt y^{-1}, respectively. The IFBR selected in Saskatchewan uses 100 % of DW; however, the IFBR located in British Columbia valorizes LR.

Operational constraints influence significantly the capacity to satisfy the entire demand, the locations and capacities of the IFBR as well as the proportion of forest biomass type used (Table 7-1).

For the synthesis of biomethanol in Eastern Canada, the IFBR located in Ontario (PE2), Quebec (PE7, PE11) and New Brunswick (PE14) remain unchanged by introducing operational constraint, however, two additional IFBR, both located in New Brunswick, (PE15 and PE17) are added. As the number of IFBR increases and the forest biomass available decreases, the minimum production capacity decreases from 1.17 Mt y^{-1} to 0.63 Mt y^{-1} while the upper limit remains unchanged and is estimated at 1.85 Mt y^{-1}. In this scenario, 55 % of the biomethanol demand is produced in Quebec and Ontario with respectively 39 % and 16 % whereas the rest is

produced in New Brunswick. In total, LR is used to satisfy 71 % of the demand while the rest is supplied by DW valorised in PE7.

On the other hand, to satisfy the biomethanol demand in Western Canada, The IFBR, identified in PW13 remains unchanged, however, PW17 is replaced by PW15 (British Columbia) due to the presence of abundant DW resources. In total, 78 % of the biomethanol demand comes from LR valorised in PW13 while the remaining is supplied from DW used in PW15.

The biomethanol production cost does not change significantly with region (Fig. 7-2). In Eastern Canada, the biomethanol production cost is estimated at 967 $ t^{-1} while in the western part, the optimal biomethanol production costs is 963 $ t^{-1}. In general, the change of the locations from Western to Eastern Canada increases the biomethanol production only by 0.4 %.

As shown in Fig. 7-2, storage and production costs represent the significant cost part with 47 % and 72 % respectively in Eastern and Western Canada. The transportation costs are lower when biofuels are produced in the Western Canada than in the eastern part. This is due to the higher distance between PM and petroleum refineries in the latter case. The costs related to forest biomass procurement and transportation remain unchanged irrespective of the locations of the IFBR. They account for about 9 % of the total biomethanol costs. This is because a restricted procurement radius of 150 km is assumed in this study. Taking into account profits from natural gas substitution, co-products selling, government incentives and carbon pricing program, a saving of about 6 % and 3 % of the biomethanol production cost in Eastern and Western part of Canada, respectively is observed.

By introducing operational constraint, results show that the biomethanol production cost is more influenced by biomass availability when biomethanol is produced in Eastern Canada than in the Western part. In fact, the biomethanol production cost increases by 15.5 % and 2.8 % respectively in Eastern and Western Canada.

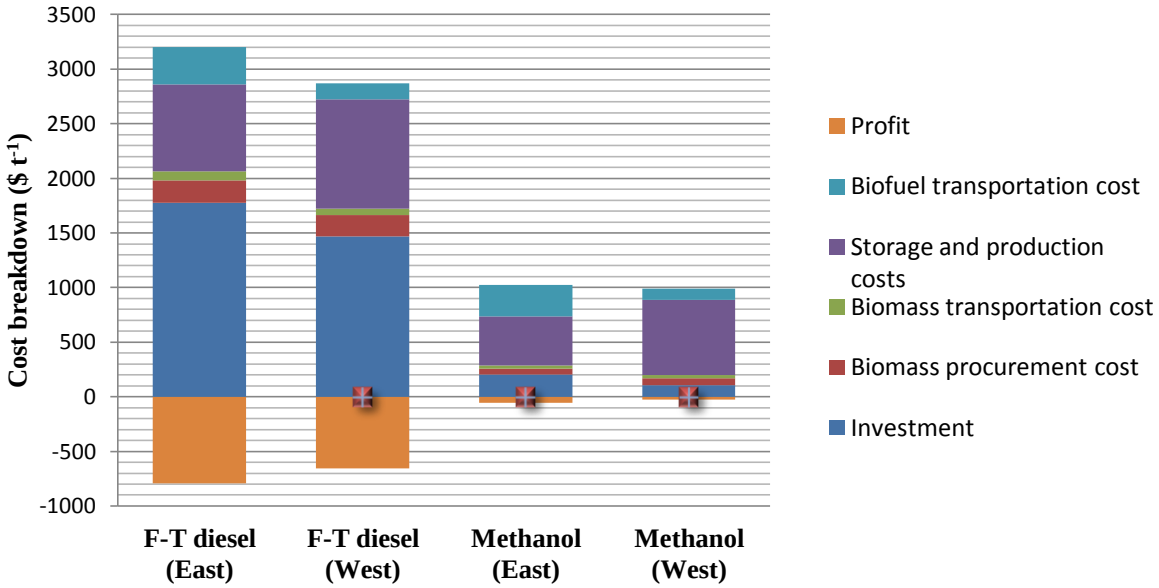


Figure 7-2: Biofuels production costs in Eastern and Western Canada (EC: Eastern Canada, WC: Western Canada)

Table 7-1: Optimal locations and capacities of the potential integrated forest biorefineries for biomethanol synthesis and the corresponding biomass feedstock used for in scenario 1

Receptor pulp mill	**Capacity of the integrated forest biorefinery (Mt y^{-1})**	**Biomass feedstock used (%)**	
		LR	**DW**
Biomethanol synthesis in Eastern Canada			
100 % recovery rate			
PE2	1.85	100	0
PE7	1.79		
PE11	1.17		
PE14	1.17		
52 % recovery rate			
PE2	1.00	71	29
PE 7	1.85		
PE 11	0.63		
PE 14	0.93		
PE 15	0.84		
PE 17	1.15		
Biomethanol synthesis in Western Canada			
100 % recovery rate			
PW13	1.15	51	49
PW17	1.12		
52 % recovery rate			
PW13	1.15	78	22
PW15	1.12		

7.5.1.2 **Scenario 2: Economic and environmental optimization of the biomethanol supply chain**

Results show that doubling the biomethanol demand in Eastern Canada will require the construction of seven IFBR. Four are integrated into the same PM as for scenario 1 (PE2, PE7, PE11 and PE14) while three are added in Quebec (PE9) and New Brunswick (PE5 and PE17). The production capacity increases and ranges from 0.95 Mt y^{-1} to 3.4 Mt y^{-1}. In total, 58 % of the demand is satisfied from the IFBR located in Quebec and Ontario (with respectively 43 % and 15 %) whereas the rest is produced in New Brunswick. In this scenario, most of the IFBR valorize LR except the IFBR implanted in PE7 which uses only DW to produce 27 % of the entire demand. The optimal locations and capacities of the IFBR as well as the percentage of each biomass feedstock used are given in Table 7-2. The biomethanol production cost is estimated at 1085 \$ t^{-1}. It is raised by only 12 % compared to scenario 1. The reason is that, by increasing the number of the IFBR involved, the investment cost is higher; however, the biomethanol transportation cost decreases significantly.

For biomethanol production in Western Canada, the locations of the IFBR (PW13 and PW17) as well as the feedstock type valorized remain unchanged by doubling the biomethanol demand. This is due to the presence of significant forest biomass resources in the selected IFBR. The production capacities are however increased to about 3.2 Mt $y^{-1}$and 1.3 Mt y^{-1} respectively for PW13 and PW17. Overall, 70 % of the demand is satisfied from LR while 30 % is from DW valorized in PW17. In this scenario, the biomethanol production cost is decreased from 963 \$ t^{-1} to 834 \$ t^{-1} due to the economy of scale.

Scenario 2 takes into account the economic and environmental objectives presented in terms of production cost, GHG emissions and fossil fuel consumptions of the biomethanol supply chain. The objective of simultaneously minimizing the production cost and the GHG emissions is firstly considered. The Pareto curves revealing the trade-offs between the two objectives are presented in Fig. 7-3 for biomethanol synthesis in Eastern and Western Canada. By comparing the solutions presented in red, we can identify a minimum cost solutions (solutions A), a minimum GHG emissions solutions (solutions B) and a good choice solutions (solutions C). The

solutions C, representing a good compromise between solutions A and B, are constructed in such a way that we reduce the GHG emissions with only a small increase in the minimum cost solutions.

We can see that the good choice solutions yield a slightly higher production costs of 1086 \$ t^{-1} and 847 \$ t^{-1} while they reduce the GHG emissions by about 15 % and 35 % respectively in Eastern and Western Canada. We can also seen that from solutions to solutions B, the GHG emissions have been reduced to 2786 kg CO_{2e} t^{-1} and 2587 kg CO_{2e} t^{-1} while the minimum production cost have been increased to 1097 \$ t^{-1} and 1094 \$ t^{-1} respectively in Eastern and Western Canada. We note that the optimal numbers and locations of IFBR for solutions B and C are the same as for solution A, although the choice of feedstock has been changed. Results show that from solution A to solution B, the quantity of LR used has been reduced while the amount of DW has been increased. Such decisions lead to lower GHG emissions since from environmental perspective DW has better performance than LR (16).

Trade- offs between the economic objective and the fossil fuel consumptions objective have also been addressed (Fig. 7-4). We can see that as the unit production costs increase from solutions A to solutions B, the unit fossil fuel consumptions decrease. Results show that this change does not modify the number and locations of the IFBR in Eastern Canada while, in Western Canada, it implies the implementation of three additional IFBR in PW2, PW15 and PW16 and the elimination of the IFBR sited in PW13. This is because reducing the transportation distance due to increasing the number of IFBR leads to a significant reduction of the total fossil fuel consumptions. Results show also that, by considering fossil fuel consumptions, the preferred feedstock type changes from LR to DW. Such decision is mainly due to the lower fossil fuel consumptions of DW procurement compared to LR treatment (16).

Table 7-2: Optimal locations and capacities of the potential integrated forest biorefineries for biomethanol synthesis and the corresponding biomass feedstock used for scenario 2

Receptor pulp mill	**Capacity of the integrated forest biorefinery (Mt y^{-1})**	**Biomass feedstock used (%)**	
		LR	**DW**
Biomethanol synthesis in Eastern Canada			
PE2	1.85	73	27
PE 7	3.42		
PE 9	0.95		
PE 11	1.17		
PE 14	1.72		
PE 15	1.55		
PE 17	2.11		
Biomethanol synthesis in Western Canada			
PW13	3.18	70	30
PW 17	1.30		

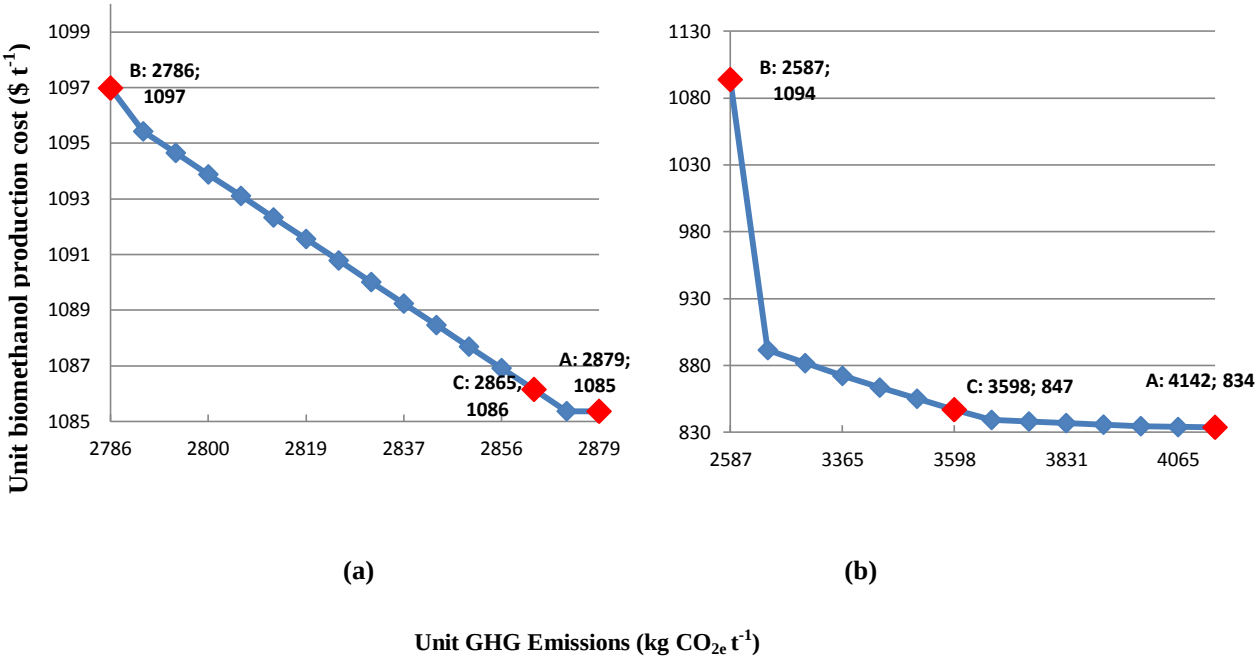


Figure 7-3: Pareto curve showing trade-offs between production costs and GHG emissions for biomethanol production in (a) Eastern Canada, (b) Western Canada (A: solution with minimal production cost, B: solution with minimal GHG emissions, C: good choice solution)

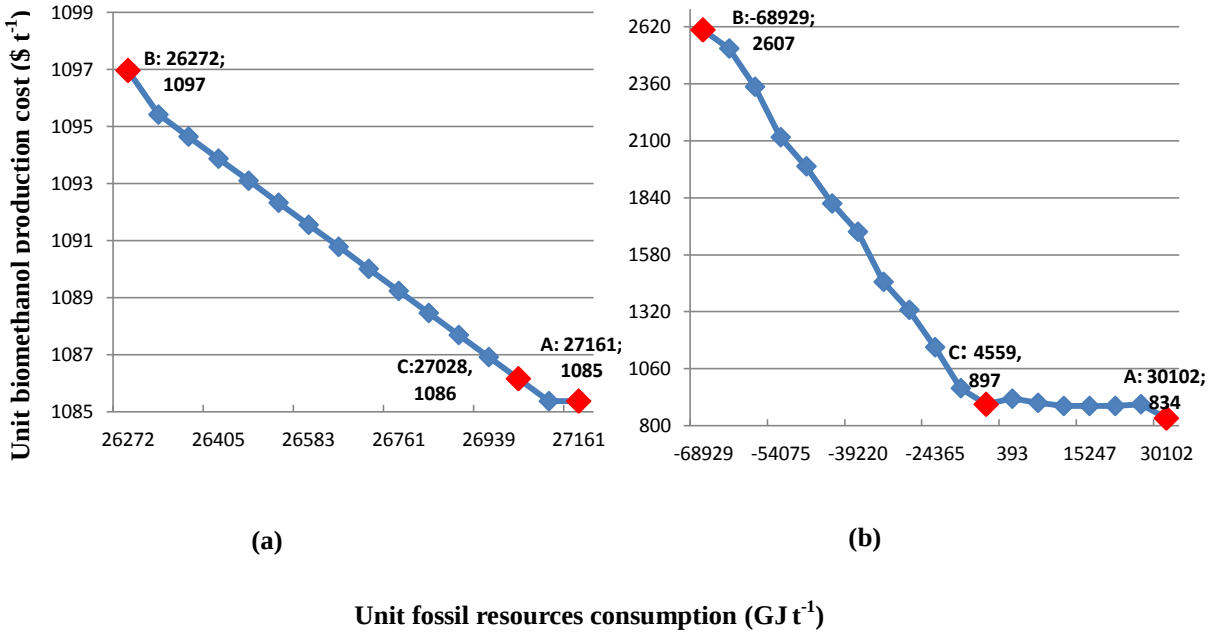


Figure 7-4: Pareto curve showing trade-offs between production cost and fossil resources consumptions for biomethanol production in (a) Eastern Canada, (b) Western Canada, (A: solution with minimal production cost, B: solution with minimal fossil fuel consumptions, C: good choice solution)

7.5.2 Case study 2: F-T diesel synthesis

7.5.2.1 Scenario1: Economic optimization of the F-T diesel supply chain

For the production of F-T diesel in Eastern Canada, five IFBR are selected. The IFBR located in PE2, PE7 and PE14, remain unchanged irrespective of biofuel type, however, PE11 is replaced by PE15 and PE17, both located in New Brunswick. Because of the biomass capacity limit and the F-T process efficiency, smaller production capacity ranging from 0.35 Mt y^{-1} to 0.84 Mt y^{-1} is reported for F-T synthesis. Results show that Quebec and Ontario can satisfy 50 % of the F-T diesel demands (respectively 32 % and 18 %) whereas the rest is produced in New Brunswick. As shown in Table 7-3, most of the selected IFBR use 100 % LR except the IFBR located in PE7 which valorizes DW to satisfy 32 % of the demand.

For the production of F-T diesel in Western Canada, the same integrated IFBR selected for the synthesis of biomethanol are identified (PW13 and PW17), however, two additional plants are added in Alberta (PW2) and in British Columbia (PW15). In this scenario, the production capacity varies from 0.35 Mt y^{-1} to 0.68 Mt y^{-1}. In total, 81 % of the F-T demand is satisfied from the IFBR located in British Columbia and Saskatchewan with (respectively 57 % and 24 %) whereas the remaining is produced in Alberta. In Western Canada, 62 % of the total F-T diesel demand is satisfied from DW used in PW2, PW15 and PW17 while the rest from comes from LR valorised in PW13.

By considering operational constraints for the production of F-T diesel in Eastern Canada, the feedstock available becomes lower than the quantity required to satisfy the entire demand of scenario 1 hence, the implantation of the IFBR is infeasible.

The entire demand of F-T diesel in Western Canada is satisfied from the IFBR located in British Columbia, which are PW13, PW6, PW9 and PW10. In this scenario, the production capacity varies between 0.35 Mt y^{-1} to 0.56 Mt y^{-1}. In total, DW valorised in PW6 and PW10 satisfies about 58 % of the demand while the rest comes from LR used in PW9 and PW13 (Table 7-3).

The production cost of F-T diesel is different for the Eastern and Western part of Canada (Fig. 7-2). In the Western Canada, the F-T diesel production costs is estimated at 2216 \$ t^{-1} while in the eastern part, the optimal production costs is about 2411 \$ t^{-1}. In general, the change of the locations from Western to Eastern Canada increases the F-T diesel production cost by about 8.8 %.

Table 7-3: Optimal locations and capacities of the F-T diesel base biorefineries and the corresponding biomass feedstock used for scenario 1

Receptor pulp mill	**Capacity of the integrated forest biorefinery (Mt y^{-1})**	**Biomass feedstock used (%)**	
		LR	**DW**
F-T diesel synthesis in Eastern Canada			
PE2	0.45	68	32
PE7	0.84		
PE14	0.42		
PE15	0.35		
PE17	0.52		
F-T diesel synthesis in Western Canada			
100 % recovery rate			
PW2	0.35	38	62
PW13	0.68		
PW15	0.35		
PW17	0.43		
52 % recovery rate			
PW6	0.56	42	58
PW 9	0.35		
PW 10	0.45		
PW 13	0.45		

As shown in Fig. 7-2, the investment cost is the major cost part for F-T diesel production, accounting for 74% and 66% of the total cost, respectively in the Eastern and Western Canada. These results suggest that improving the F-T process in order to increase the IFBR capacities is the key issue to overcome the barrier of commercializing F-T diesel. The transportation costs are lower when biofuels are produced in the Western Canada than in the eastern part. This is due to the higher distance between PM and petroleum refineries in the latter case. As for biomethanol case study, the costs related to forest biomass procurement and transportation remain unchanged irrespective of the locations of the IFBR (12 % of the total F-T diesel production cost). This is because a restricted procurement radius of 150 km is assumed in this study. Taking into account profits from natural gas substitution, co-products selling, government incentives and carbon pricing program, a considerable saving of about 30 % and 33 % of the production cost is shown for F-T diesel synthesis in Eastern and Western Canada, receptively.

By introducing operational constraint, results show that F-T diesel production cost increases by 6.9 % in Western Canada.

7.5.2.2 **Scenario 2: Economic and environmental optimization of the F-T diesel supply chain**

Model results show that the implantation of the IFBR to satisfy the entire F-T diesel demand in Eastern Canada is infeasible. This is due to the insufficient feedstock quantity available within the fixed radius.

F-T diesel synthesis in Western Canada involves the construction of six IFBR. Three are integrated into the same PM as for the scenario 1 (PW13, PW15 and PW17) while three others are added in Alberta (PW3) and British Columbia (PW6, PW8). The production capacity varies from 0.38 Mt y^{-1} to 1 Mt y^{-1}. Of the total, 89 % of the biomethanol demand is satisfied from the IFBR located in British Columbia and Saskatchewan (with 78 % and 11 % respectively) whereas the remaining is produced in Alberta. In this scenario, DW is the most used feedstock. LR is only valorized in PW13 to satisfy 23 % of the demand. The optimal locations and capacities of the IFBR as well as the percentage of each biomass feedstock used are given in Table 7-4. Results show that the F-T diesel production cost has not significantly changed by doubling the demand

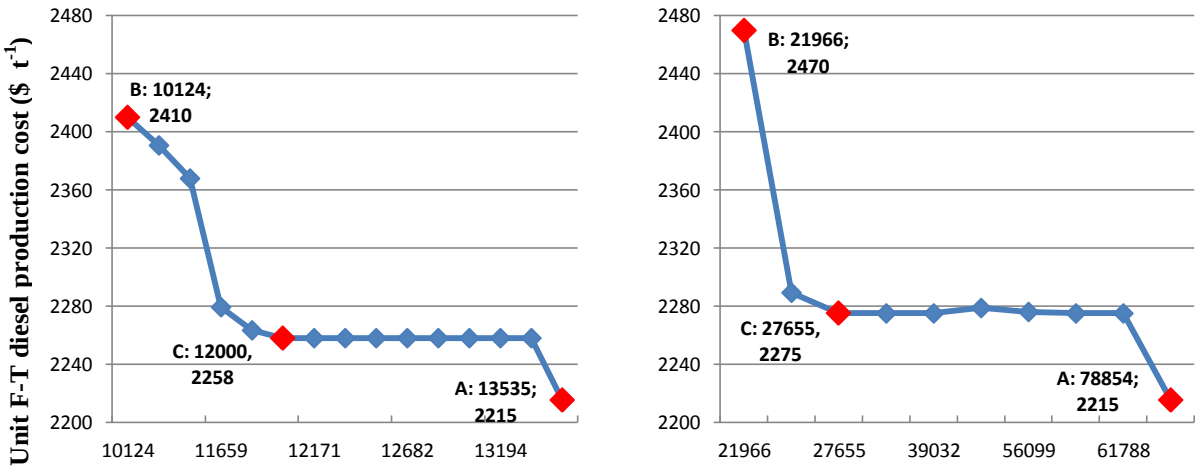
level since it passes from 2215 \$ t^{-1} to only 2216 \$ t^{-1}. The reason is that, by increasing the number of the IFBR, the investment cost rises while the F-T diesel transportation cost decreases significantly.

The Pareto curve revealing the trade-offs between the production cost and the GHG emissions for F-T diesel synthesis is presented in Fig. 7-5.a. For the good choice solution (solution C), the reduction of the GHG emissions from 13535 kg CO_{2e} t^{-1} to 12000 kg CO_{2e} t^{-1}implies an increase of the unit production cost from 2216 \$ t^{-1} to about 2258 \$ t^{-1}. This reason it that, in this particular point, the IFBR identified in PW8 is replaced by PW9 which valorizes DW instead of LR.

The trade-offs between the economic objective and the fossil fuel consumptions objective has also been studied as shown in Fig. 7-5. b. The unit production costs of F-T diesel in solutions A, C and B are 2215 \$ t^{-1}, 2275 \$ t^{-1} and 2470 \$ t^{-1}, respectively, while their corresponding unit fossil fuel consumptions are 78854 GJ t^{-1}, 27655 GJ t^{-1}, and 21966 GJ t^{-1}, respectively. Results indicate that by considering the fossil fuel consumption objective, the IFBR located in PW8 and PW13 have been replaced by PW2 and PW10. Such locations decisions are mainly due to initial changes in feedstock input through the substitution of LR by DW. As a result, the GHG emission of the F-T supply chain is reduced.

Table 7-4: Optimal locations and capacities of the integrated forest biorefineries and the corresponding biomass feedstock used for scenario 2

Receptor pulp mill	**Capacity of the integrated forest biorefinery (Mt y^{-1})**	**Biomass feedstock used (%)**	
		LR	**DW**
F-T diesel synthesis in Western Canada			
PW 3	0.38	23	73
PW 6	1.04		
PW 8	0.42		
PW 13	0.83		
PW 15	0.52		
PW 17	0.43		



(a) **(b)**

Figure 7-5: Pareto curve showing trade-offs between the production costs and the envormental performances of the F-T diesel supply chain in Western Canada: (a) unit GHG emissions (kg CO_{2e} t^{-1})**,** (b) unit fossil resources consumption (GJ t^{-1})

7.6 Discussion

The analysis of the results indicates that Eastern and Western Canada could be self-sufficient in the production of biomethanol as a fuel additive in gasoline up to 10% (about 13 Mt y^{-1} and 5 Mt y^{-1} in Eastern and Western Canada respectively). In addition, results show that Western Canada have a potential to produce up to 3.7 Mt y^{-1} of F-T diesel which can meet the demand for about 4 % blending with diesel. However, the limitation of the forest biomass availability and the high diesel demand in Eastern Canada as well as the low efficiency of the F-T process make the implantation of the IFBR to satisfy 4% of the eastern diesel demand with F-T diesel infeasible (estimated at 5.22 Mt y^{-1}). Spruce budworm, recognized as one of the most destructive native insects in the northern spruce-fir forests of Eastern Canada and affecting about 1.6 million hectares per year on average between 2001 and 2011 (37, 38), could be added to LR and FDS in order to attain the F-T diesel target of 4 % in Eastern Canada.

The biomethanol-based biorefineries valorizes mainly LR feedstock while DW are considered only when LR are fully exploited. Due to the low efficiency of the F-T process, The F-T diesel-based biorefineries have relatively small capacities in comparison to biomethanol-based biorefineries. In addition, they utilize mainly DW feedstock which makes the supply chain of the F-T diesel synthesis riskier in terms of long-term stability and logistics as this feedstock is more uncertain due to the variability of wildfires (39-41). However, the advantage of using different forest biomass or the production of biomethanol and F-T diesel is that biofuels could be produced jointly.

The results show also that operational constraint and demand level considerations have a significant impact on the potential IFBR locations and the biofuels production costs in Eastern and Western Canada. Results reveled that the biomethanol production cost in Eastern Canada is more sensitive to biomass availability than to demand level while in the western region, it varies primarily with demand level. In addition, results indicate that F-T diesel production cost is Western Canada is more influenced by biomass availability than by doubling the demand.

The results of the eastern and western case studies have some similarities. For instance, IFBR are usually located in provinces with abundant forest biomass resources and are closer to the

petroleum refineries (ON and QC for Eastern Canada, BC and SK for Western Canada). Nonetheless, by introducing operational constraint or by increasing the demand, additional IFBR are added in provinces with significant forestry activities since the forest biomass available becomes fully exploited. In addition, results revealed that Western Canada implies the implementation of a smaller distributed network (limited number) of IFBR with smaller capacity compared to Eastern Canada. This is because, in western regions, lower biofuels demands are required while higher forest biomass amount is available.

By considering environmental objectives in the eastern case study, the GHG emissions as well as the fossil resources consumption related to the biomethanol supply chain are significantly reduced without affecting the production cost and the optimal locations of the IFBR. For western case study, the objective of reducing the GHG emissions implies change in the optimal network of only F-T diesel-based biorefineries while the objective of reducing the fossil resources consumption loads to a change in the optimal networks of the two selected biofuels-based biorefineries.

7.7 Conclusion

The objective of this study was to design of the IFBR supply chains in order to optimize the biofuels production costs and reduce the GHG emissions and the fossil resources consumption.

To achieve this objective, a multicriteria optimization model has been developed which takes into account two feedstock type, forest biomass sources availability, stored biomass degradation with time, harvesting seasonality, petroleum refineries demands, carbon pricing program as well as government incentives. Through this model, the most suitable PM to be transformed into IFBR in order to satisfy the Eastern and Western Canada biofuels demand are found. Furthermore, optimal network design, capital investment, production operations costs, capacity, forest biomass type used as well as petroleum refineries supplied are determined for each IFBR.

The multicriteria optimization problem is solved with an Epsilon-constraint method, and the results have revealed the trade-offs among the economics and environmental performances of the biofuels supply chains.

The application of the proposed model is illustrated through two case studies representative for biomethanol and F-T diesel synthesis as options for gasoline and diesel blending respectively. For each case study, The IFBR supply chains in Eastern and Western Canada are compared when the biomethanol and F-T diesel are used to supply 5% of the current gasoline usage and 2 % of the fossil diesel usage, respectively, based on the existing blending requirement in Canada. Then, a doubled biofuel blending requirement has been assumed.

The models presented in this paper were found to be a useful tool to compare the supply chains of biomethanol and F-T diesel synthesis in Eastern and Western Canada, to identify the most promising forest biomass resources and to find the parameters that affect the design of biomass supply chains in terms of location and number of eligible IFBR and their potential capacities. Nonetheless, the proposed models adopt a deterministic approach. They do not consider uncertainty in biomass supply, biofuel demand, conversion technology efficiency, etc. Investigating the impacts of different types of uncertainty and risks in future research will be of significant importance to the design and operations of robust biofuels supply chains.

Future research direction is to implement a nation-level case study that takes into account biomass and biofuels import and export.

7.8 Acknowledgements

This work was supported by BioFuelNet Canada and by the MITACS Accelerate Program.

7.9 **Appendix**

Table A.1: Petroleum refineries demands for biomethanol and F-T diesel

Refineries	Location	Refining capacity[18] ($Mt\ y^{-1}$)	F-T diesel demand[19] ($Mt\ y^{-1}$)	Biomethanol demand[20] ($Mt\ y^{-1}$)
Eastern Canada				
Id1	Saint John (NB)	116	0.56	1.92
Id2	Valero (QC)	96.7	0.46	1.60
Id 3	Montreal (QC)	50.0	0.24	0.83
Id 4	Corunna (ON)	27.4	0.22	0.27
Id 5	Jarvis (ON)	40.9	0.33	0.41
Id 6	Sarnia (ON)	44.2	0.35	0.44
Id 7	Mississauga (ON)	6.20	0.25	0.31
Id 8	Sarnia (ON)	31.0	0.20	0.69
Western Canada				
Id 1	Prince George (BC)	4.38	0.04	0.04
Id 2	Burnaby (BC)	20.8	0.17	0.21
Id 3	Regina (SK)	47.0	0.38	0.47
Id 4	Edmonton (AB)	51.8	0.41	0.52
Id 5	Saskatchewan (AB)	36.5	0.29	0.37
Id 6	Edmonton (AB)	68.3	0.55	0.68

[18] The refining capacities are obtained from14. The Canadian Fuels Association. The Economics of Petroleum Refining. Understanding the business of processing crude oil into fuels and other value added products Canada2013 [11-12-2017]. Available from: http://www.canadianfuels.ca/website/media/PDF/Publications/Economics-fundamentals-of-Refining-December-2013-Final-English.pdf..The crude oil produced contains 40% distillate and 20% gasoline in Western Canada and Ontario (heavy oil are produced in these countries). For Eastern Canada except Ontario (when light oil imported) , crude oil content is 24 % of distillate and 33% of gasoline.

[19] F-T Diesel demand is estimated at 2 % of the diesel produced,

[20] Methanol demand is estimated at 5 % of the gasoline produced.

Table A.2: Purchased equipment costs for biomethanol and F-T diesel synthesis (M$)

Description of cost	Purchased equipment costs for biomethanol synthesis (M$)	Purchased equipment costs for F-T diesel synthesis (M$)
Air separation unit	14	9
Feed handling &drying	16	10
Gasification	56	16
Syngas cleaning	37	13
Fuel conditioning	NA	22
Product synthesis & separation	11	
Hydro-processing	NA	13
Power generation	15	17
Balance of plant	3	12
Total	150	113
References	(30)	(29)

Methanol and F-T diesel purchased equipment costs calculation are based on 0.31 Mt y^{-1} and 0.15 Mt y^{-1} capacities, respectively. All capital costs are reported in 2015 Canadian dollars. Equipment cost escalation is calculated by using the chemical engineering plant cost index.

Table A.3: list of sets, parameters and variables of the optimization model

Set		
B	Set of forest biomass sources indexed by b	
U	Set of biofuel process units indexed by u	
T	Set of time period indexed by t	
L	Set of capacity level indexed by l	
I	Set of forest biomass procurement sites indexed by i	
J	Set of PM sites indexed by j	
K	Set of petroleum refineries locations indexed by k	
Q	Set of by-product types indexed by q	
Parameters		
Drd (j,k)	Distance between the integrated forest biorefinery located in 'j' and the petroleum refineries 'k'	(km)

Dbr (i,j)	Distance between the forest biomass procurement site 'i' and the integrated forest biorefinery 'j'	(km)
Bq (b,i,t)	Quantity of forest biomass 'b' available in the FB procurement site 'i' at period time 't'	(odt)
Df (k,t)	Biofuel demand of the petroleum refineries 'k' at time period 't'	(t)
Ngu (j)	Annual natural gas use of the integrated forest biorefinery located in 'j'	(t)
Wf (i,t)	Weather factor for harvesting in procurement site 'i' at period time 't'	
Rr (b,i,t)	Recovery rate of forest biomass 'b' harvested in procurement site 'i' at time period 't'	(%)
Db (b,t)	Percentage of deteriorated forest biomass 'b' at time period 't'	(%)
El	Economical Lifetime	(y)
Ir	Interest Rate	(%)
Ef (b)	Conversion factor of the forest biomass 'b'	(t odt^{-1})
Mp	Minimum production amount as a percentage of the annual capacity of the integrated forest biorefinery	(%)
Dp (t)	Duration of the time period	day
Pa	Production time duration of a year	day
Bpef (q)	Conversion factor for the synthesis of the by-product 'q'	(t odt^{-1})
Up (l)	Upper bound of the integrated forest biorefinery capacity with the capacity level 'l'	(t)
Lo (l)	Lower bound of the integrated forest biorefinery capacity with the capacity level 'l'	(t)
Gimax	Maximum allowable incentive amount	($)
Giper	Maximum percentage of the capital cost that can be covered by incentive	(%)
Mcap	Minimum plant capacity	(t)
Ic (l)	Investment cost with the capacity level l	($)
Fcc	Fixed conversion cost	($ t^{-1})
Vcc	Variable conversion cost	($ t^{-1})
Fftc	Fixed biofuel transportation cost	($ t^{-1})
Vftc	Variable biofuel transportation cost	($ t^{-1} km^{-1})
Fbtc (b)	Fixed biomass transportation cost	($ odt^{-1})
Vbtc (b)	Variable biomass transportation cost	($ odt^{-1} km^{-1})
Sfc (j)	Biofuel storage cost in the integrated forest biorefinery 'j'	($ t^{-1})
Sbc (b,j)	Storage cost of the forest biomass 'b' in the integrated forest biorefinery 'j'	($ odt^{-1} day^{-1})
Cb (b,i)	Procurement cost of the forest biomass type 'b' from the site 'i'	($ odt^{-1})

Pbc (q)	Selling price of the by-product 'q'	($ t^{-1})
Png	Natural gas purchased cost	($ t^{-1})
Eb (b,i)	GHG emissions related to procuring forest biomass 'b' from site 'i'	(kg CO_{2e} odt^{-1})
Etb (b)	GHG emissions related to transporting forest biomass 'b'	(kg CO_{2e} km^{-1} odt^{-1})
Esb (b)	GHG emissions related to storing forest biomass 'b'	(kg CO_{2e} odt^{-1})
Esf	GHG emissions related to storing biofuel	(kg CO_{2e} t^{-1})
Etf	GHG emissions related to transporting biofuel	(kg CO_{2e} km^{-1} t^{-1})
Epf	GHG emissions related to producing biofuel	(kg CO_{2e} t^{-1})
Ebp (q)	GHG emissions avoided from producing by-products 'q'	(kg CO_{2e} t^{-1})
Eng	GHG emissions avoided from substituting natural gas	(kg CO_{2e} t^{-1})
Eaf	GHG emissions avoided from substituting fossil fuel	(kg CO_{2e} t^{-1})
Rpb (b,i)	Fossil resources consumption related to procuring forest biomass 'b' from site 'i'	(MJ odt^{-1})
Rtb (b)	Fossil resources consumption related to transporting forest biomass 'b'	(MJ $km^{-1}odt^{-1}$)
Rtf	Fossil resources consumption related to transporting biofuel	(MJ km^{-1} t^{-1})
Rpf	Fossil resources consumption related to producing biofuel	(MJ t^{-1})
Rbp (q)	Fossil resources consumption avoided from producing by-products 'q'	(MJ t^{-1})
Rng	Fossil resources consumption from substituting natural gas	(MJ t^{-1})
Raf	Fossil resources consumption from substituting fossil fuel	(MJ t^{-1})
Binary variables		
Yb (b,i,j,t)	1 if forest biomass 'b' is transported from site 'i' to the integrated forest biorefinery located in 'j' at time period 't'	
Yc (j,l)	1 if the capacity level 'l' is chosen for the integrated forest biorefinery located in 'j'	
Continuous variables		
Hb (b,i,t)	Quantity of forest biomass 'b' procured from site 'i' at time period 't'	(odt)
Tb (b,i,j,t)	Quantity of forest biomass 'b' transported from site 'i' to the integrated forest biorefinery 'j' at time period 't'	(odt)
Ub (b,j,t)	Quantity of forest biomass 'b' used in the integrated forest biorefinery located in 'j' at time period 't'	(odt)
Sb (b,j,t)	Quantity of forest biomass 'b' stored in the integrated forest biorefinery located in 'j' at time period 't'	(odt)
Pf (j,t)	Quantity of biofuel produced in integrated forest biorefinery located in 'j' at time period 't'	(t)
Tf (j,k,t)	Quantity of biofuel transported from the integrated forest biorefinery	(t)

	located in 'j' to the petroleum refineries 'k'	
Sf (j,t)	Quantity of biofuel stored in the integrated forest biorefinery located in 'j' at time period 't'	(t)
Capl (j,l)	Annual production capacity of the integrated forest biorefinery located in 'j' with capacity level l	(t y^{-1})
Cap (j)	Annual production capacity of the integrated forest biorefinery located in 'j'	(t y^{-1})
Pbp (j,q,t)	Quantity of byproduct 'q' produced in the integrated forest biorefinery located in 'j' at time period 't'	(t)
Ginc (j)	Annual incentive from the government to the integrated forest biorefinery located 'j'	($ y^{-1})
Tc	Total annual cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tic (j)	Total investment cost of the integrated forest biorefinery located in 'j'	($)
Tac (j)	Total annualized investment cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tbpc (j)	Total annual biomass purchased cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tbtc (j)	Total annual biomass transportation cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tbsc (j)	Total annual biomass storage cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tcc (j)	Total annual conversion cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tfsc (j)	Total annual biofuel storage cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tftc (j)	Total annual biofuel transportation cost of the integrated forest biorefinery located in 'j'	($ y^{-1})
Tbyc (j)	Total annual credit from selling by-products in the integrated forest biorefinery located in 'j'	($ y^{-1})
Tngc (j)	Total annual credit from subtitling natural gas in the integrated forest biorefinery located in 'j'	($ y^{-1})
Tbpe (j)	Total annual GHG emissions related to forest biomass procurement in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tbte (j)	Total GHG emissions related to forest biomass transportation in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tbse (j)	Total GHG emissions related to forest biomass storing in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tfpe (j)	Total GHG emissions related to biofuel production in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tfse (j)	Total GHG emissions related to biofuel storing in the integrated forest	(kg CO_{2e} y^{-1})

	biorefinery located in 'j'	
Tfte (j)	Total GHG emissions related to biofuel transportation in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tbye (j)	Total GHG emissions from producing by-product in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tnge (j)	Total GHG emissions from substituting natural gas in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Tfae (j)	Total GHG emissions related to biofuel substituting in the integrated forest biorefinery located in 'j'	(kg CO_{2e} y^{-1})
Te	Total GHG emissions	(kg CO_{2e} y^{-1})
Tbpr (j)	Total fossil resources consumption related to biomass procurement in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tbtr (j)	Total fossil resources consumption related to forest biomass transportation in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tfpr (j)	Total fossil resources consumption related to biofuel production in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tftr (j)	Total fossil resources consumption related to biofuel transportation in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tbyr (j)	Total fossil resources consumption from producing by-product in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tngr (j)	Total fossil resources consumption from substituting natural gas with syngas in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tfar (j)	Total fossil resources avoided related to biofuel substituting in the integrated forest biorefinery located in 'j'	(MJ y^{-1})
Tr	Total fossil resources consumption	(MJ y^{-1})

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CHAPITRE 8 DISCUSSION GÉNÉRALE

8.1 Faisabilité économique du concept de la bioraffinerie forestière intégrée et verte

Dans le cadre du développement du concept de la BRFIV, l'intégration de bioraffineries basées sur la gazéification de la biomasse aux usines papetières est justifiée. En effet, le gaz de synthèse produit est capable de supprimer tout usage de ressources fossiles dans les usines papetières qui sont de grandes consommatrices de combustibles fossiles.

Les données économiques et techniques utilisées pour évaluer la viabilité économique des options de valorisation du gaz de synthèse proviennent principalement de rapports réalisés par le DOI et le NREL. Quoique ces données soient suffisantes pour établir une analyse comparative des options, une simulation des procédés de production des alternatives considérées pourrait être envisagée afin de comparer les données d'entrée.

Les résultats obtenus démontrent que le concept de la bioraffinerie intégrée et verte ne peut être économiquement viable que par la diversification de la gamme de produits issus du gaz de synthèse. L'analyse démontre également que, comparativement à la production du diesel F-T, l'ammoniac et l'éthanol, la production du méthanol constitue la meilleure option d'un point de vue économique. De plus, la production peut être orientée selon le jeu de l'offre et la demande vers la synthèse d'autres produits tels que le DME.

Les coûts d'investissement relatifs à la conversion de la biomasse en bioproduits ont été estimés selon la méthode de similitude et ajustés selon l'année de référence. On a fait l'hypothèse que les unités de références et celles estimées sont de conception similaire et que l'écart de capacité n'entraine pas des modifications significatives de l'installation. Une analyse de sensibilité relative aux coûts d'investissements a été réalisée afin de considérer cette hypothèse.

La faisabilité du concept est démontrée pour un cas d'étude correspondant à une usine de pâte dissoute. Les résultats ne peuvent pas être généralisés pour tous types d'usines papetières car les besoins en ressources fossiles varient d'un procédé à un autre.

8.2 Analyse environnementale de la bioraffinerie de gazéification

Le développement du concept de la bioraffinerie forestière s'insère dans un contexte de développement durable. Dans ce projet, l'analyse de cycle de vie vient quantifier les émissions de GES et les ressources fossiles de dix alternatives de chaîne de valeur et propose la configuration optimale qui minimise les impacts environnementaux retenus. Il faut noter que dans cette étude, les options de chaîne logistique définies ne comprennent pas les entités de stockage de la biomasse et des bioproduits. En effet, on a fait l'hypothèse que la biomasse peut être utilisée une fois récoltée et que les impacts environnementaux du stockage des biocarburants sont négligeables. Cette hypothèse est justifiée puisque que le but de l'analyse de cycle de vie dans ce projet est de comparer les performances environnementales de scenarios envisageables, donc les processus élémentaires semblables peuvent être éliminés.

Les résultats démontrent que le choix optimal de la source de biomasse, du système de traitement de la matière première ainsi que de la forme sous laquelle elle est transportée conduit à des réductions importantes des impacts environnementaux de la chaîne logistique de la bioraffinerie forestière en ce qui concerne les émissions de GES et la consommation de ressources fossiles. Ceci permet de mettre en avant les alternatives les plus intéressantes au niveau environnemental et celles à écarter. De plus, comparer les performances environnementales de deux bioproduits issus d'un même procédé de conversion peut orienter le choix des décideurs quant au choix du bioproduit à produire au Canada dans le cadre du développement de la BRFIV. Toutefois, les choix optimaux issus d'une analyse de cycle de vie dépendent fortement du contexte de l'étude et les résultats ne sont donc pas totalement généralisables.

8.3 Outils d'aide à la prise de décisions stratégiques et tactiques

Dans ce travail de recherche, deux outils d'aide à la décision ont été développés; le premier à un niveau stratégique et le second à un niveau tactique.

Le développement du modèle mathématique de planification stratégique est nécessaire afin de choisir les structures et les configurations des bioraffineries intégrées. En d'autres termes, il s'agit

de déterminer le nombre d'entités physiques à implémenter, leur localisation et leur capacité, le type de matière première à utiliser, l'acheminement des flux de matières à travers le réseau logistique ainsi que les marchés visés (produits, technologies, etc.). Le principal enjeu des décisions prises au niveau stratégique est d'assurer une maîtrise optimale des coûts de production. Ce modèle a permis d'explorer et d'analyser divers scénarios stratégiques au niveau de chaque entité de la chaîne logistique, afin de déterminer les alternatives capables d'optimiser les performances économiques totales des bioraffineries intégrées. Les résultats obtenus démontrent que le concept de la bioraffinerie forestière intégrée et verte est économiquement faisable si le choix de la biomasse à valoriser, de la méthode de traitement de la matière première et celui de l'usine réceptrice sont optimaux. La variation de la demande finale, de la quantité de la matière première disponible ainsi que la considération des contraintes opérationnelles de récupération de la biomasse pourraient toutefois modifier les résultats.

La gestion de la chaîne logistique au niveau stratégique, traitant les décisions à long terme reliées principalement à l'investissement, n'est pas adaptée lorsqu'on désire inclure le caractère saisonnier de la récolte de la biomasse ainsi que pour déterminer une allocation mensuelle de la production à la demande. Un outil de prise de décision basé sur un modèle de planification tactique a donc été développé dans un second lieu afin de traiter les décisions reliées à l'approvisionnement de différents types et quantités de biomasse au niveau mensuel et à la l'allocation de l'offre et la demande. De plus, en réponse aux préoccupations environnementales, des objectifs environnementaux ont été intégrés dans cet outil afin d'améliorer le rendement économique des bioraffineries intégrées tout en assurant leur viabilité environnementale.

Il est à noter que les avantages associés à la technologie de gazéification, notamment la capacité de traiter diverses sources de biomasse, justifient le choix du bois mort de feux de forêts, des déchets de récolte de bois et des résidus des scieries comme matières premières potentielles. Toutefois, bien que le bois mort d'épidémie d'insectes représente une alternative intéressante compte tenu de son abondance au Canada, cette biomasse forestière n'a pas été explorée dans cette étude en raison du manque de données relatives aux quantités disponibles (caractère imprévisible de ce type de biomasse). Cette option pourrait être envisagée en utilisant des algorithmes de résolution stochastiques.

CHAPITRE 9 CONCLUSIONS ET RECOMMANDATIONS

Le projet de recherche propose une nouvelle approche pour le développement du concept de la bioraffinerie forestière intégrée et verte. Il consiste à concevoir et à optimiser la chaîne de valeur des bioraffineries de gazéification intégrées aux usines canadiennes de pâtes et papiers.

Un outil d'aide à la décision multicritère caractérisé par un large choix de matières premières, de procédés de récupération de la biomasse forestière et de bioproduits issus de la gazéification a été développé. Cet outil est capable de déterminer, les emplacements optimaux des bioraffineries, le choix de la source de biomasse et de la méthode de récupération correspondante, le choix du bioproduit à générer, la capacité optimale de l'unité de gazéification, le réseau de distribution optimal ainsi que les flux de combustibles échangés entre les unités de la BRFIV. Il vise à améliorer la rentabilité économique ainsi qu'à la viabilité environnementale des usines papetières canadiennes à travers la conception optimale des bioraffineries de gazéification intégrées. De plus, cet outil propose des stratégies de collaboration entre les BRFIV et les industries pétrochimiques. D'autre part, il aide à mieux exploiter les réserves forestières disponibles. En effet, la biomasse lignocellulosique est une ressource limitée au regard de l'ensemble de ses usages techniquement envisageables, il est important de bien la gérer et la valoriser dans des filières rentables et performantes tant du point de vue énergétique qu'environnemental. Il contribue également à la stabilisation des gaz à effet de serre et la minimisation des consommations des ressources fossiles à travers la promotion de nouvelles sources d'énergie et de carburants plus écologiques.

D'un point de vue pratique, la conception de l'outil d'aide à la décision est fondée sur le développement d'un modèle d'optimisation multicritère couplé à une analyse de cycle de vie de scenarios de chaînes logistiques. Les critères considérés sont les coûts totaux de production, les émissions de gaz à effet de serre ainsi que la consommation des ressources fossiles évitée. Le modèle mathématique a été appliqué à deux études de cas comparant les provinces de l'est et de l'ouest du Canada et à deux types de bioraffineries de gazéification à savoir le méthanol et le diesel F-T.

Dans l’ensemble des cas, la synthèse du méthanol s’est avérée sensiblement plus performante, que l’étude soit menée du point de vue monocritère (en considérant seulement l'aspect économique) ou multicritère. Les solutions de compromis, à partir desquelles le décideur pourra effectuer un choix, ont pu être déterminées.

9.1 Contributions à l’ensemble des connaissances

La plupart des études réalisées concernant le concept de la BRFIV s'intéresse à l'optimisation des flux massiques et énergétiques des opérations de production de P&P et celles du bioraffinage. L'étude et la conception de la chaîne de valeur des bioraffineries de gazéification intégrées dans des usines de pâtes et papiers dans un contexte de BRFIV restent peu étudiées. L’originalité de cette étude réside dans le développement d'un modèle de programmation mathématique capable de considérer et d'analyser plusieurs alternatives de bioraffineries de gazéification à la fois. La résolution de ce modèle est capable d'optimiser la chaîne de valeur de ces unités depuis le choix de la matière première et de la méthode d'extraction de bois dans la région de coupe jusqu'au choix du bioproduit et du marché final. L'optimisation tient en considération, simultanément, l'aspect économique et environnemental et est appliquée au contexte Canadian. Les contributions de ce projet sont présentées avec plus de détails dans ce qui suit.

9.1.1 Optimisation multicritère de la chaîne de valeur de la BRFIV

Une des contributions est la considération de trois critères dans la conception de la chaîne de valeur de la bioraffinerie de gazéification. Un critère de nature économique et deux critères de nature environnementale. En effet, avec les préoccupations croissantes des problèmes environnementaux, notamment les émissions de GES et la consommation en ressources fossiles, il est important de prendre en compte le critère environnemental au lieu de considérer une unique fonction de coût, comme il est souvent le cas. En effet, l'optimisation de l'indicateur économique conduit à une unique solution, tandis que le fait de tenir en considération plusieurs objectifs mène à un ensemble de solutions possibles aussi bonnes les unes que les autres. Cette démarche est nécessaire pour proposer une procédure d’aide à la décision étendue et ne pas limiter l’étude à une solution qui n’est pas forcément optimale par rapport à d’autres critères.

9.1.2 Aide à la décision quant au choix du produit de bioraffinage

Dans la majorité des études réalisées, le choix du produit de bioraffinage est défini à l'avance. Dans de ce projet de recherche, il est possible de comparer les performances économiques et environnementales de deux alternatives de bioraffinage utilisant le procédé de gazéification notamment le méthanol et le diesel F-T. L'étude peut se présenter donc comme un outil d'aide à la décision quant au choix du type de bioraffinerie de gazéification à implanter dans la BRFIV.

9.1.3 Étendue de la chaîne de valeur

Une des contributions du projet concerne l'étendue de la chaîne de valeur étudiée. En effet, la matière lignocellulosique utilisée dans les bioraffineries de gazéification peut provenir de sources très variées. Il peut s'agir de bois non marchants (bois morts par des incendies ou des insectes), de résidus forestiers provenant de la récolte de bois ou bien des déchets des industries de bois [8]. Divers moyens de récolte de bois (par arbre entier, par bois entier, etc.), de traitement des résidus (broyage, mise en fagots, déchiquetage, etc.) ou de transport de la biomasse lignocellulosique existent. D'autre part, plusieurs alternatives de produit peuvent se présenter. C'est au niveau du rendement, des coûts et des émissions que se fait ressentir la différence entre les alternatives. La configuration de la chaîne logistique dépend donc de l'alternative choisie à chaque étape. Dans ce projet, divers scenarios combinant les différents types de biomasse, les méthodes de récolte de bois, de traitements des résidus de bois et de choix de produits ont été proposés et comparés. Le modèle développé a permis de sélectionner par la suite les alternatives qui assurent une valorisation optimale en termes de coûts et d'émissions.

9.1.4 Considération du bois mort comme matière première potentielle

La considération du bois mort comme matière première potentielle permet d'exploiter de nouvelles sources d'énergie et d'étudier leurs avantages économiques et environnementaux surtout que cette source de biomasse est abondante au Canada et que son utilisation dans l'industrie papetière n'est pas recommandée.

9.1.5 Caractère saisonnier de la récupération de la biomasse au Canada.

Le caractère saisonnier de la récolte de la biomasse ainsi que les contraintes opérationnelles relatives à la récupération des déchets forestiers ont été considérés et modélisés dans ce projet de recherche. Ceci permet de traiter, non seulement, les décisions reliées à la structure de la chaîne logistique des bioraffineries intégrées à long terme mais aussi de traiter les décisions reliées à l'approvisionnement de différents types et quantités de biomasse au niveau mensuel.

9.2 Recommandations pour travaux futurs

A l'issue de ce travail, un certain nombre de recommandations se présente :

- L'approche est suffisamment générique pour introduire d'autres types de biomasse, d'autres procédés de conversion ou autres bioproduits qui dans des conditions économiques différentes, pourraient s'avérer intéressants des points de vue économique et environnemental.

- D'autres critères peuvent être pris en compte dans la conception de la chaîne logistique, notamment l'aspect social présenté en termes de création d'emplois.

- L'impact du choix de la biomasse forestière (utilisée à des fins énergétiques) sur la séquestration du carbone par l'écosystème forestier n'a pas été considéré. Cet indicateur pourrait s'avérer important pour préserver la forêt (maximiser la quantité de carbone captée dans l'atmosphère) et pourrait donc être pris en compte dans l'analyse de cycle de vie.

- La quantité de la matière première disponible ainsi que la demande en biocarburants ont été modélisées comme étant des paramètres déterministes. Cependant, ces derniers peuvent varier au cours du temps. L'aspect stochastique pourra être considéré en utilisant par exemple des algorithmes Monte Carlo, avec une analyse de flexibilité.

- L'optimisation multicritère conduit à un ensemble de solutions de compromis présenté par le front de Pareto. Le décideur, en tenant compte de critères internes ou gouvernementaux, pourra favoriser une solution par rapport à d'autres. Des méthodes classiques d'aide à la décision multicritère (Topsis, Electre, Promethée…) peuvent être couplées aux résultats d'optimisation afin de fournir les solutions répondant aux critères désirés.

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ANNEXE A - SYNTHÈSE DE LA REVUE DE LA LITTÉRATURE

Références	Produit considéré	Objectif	Variables de décision	Incertitude/multipériode	Cas d'étude
Leduc et al. [36]	Méthanol et récupération de la chaleur à partir du peuplier	Économique	Emplacements des bioraffineries, capacité, logistique	Non	Autriche
Natarajan et al. [37]	Choix entre méthanol et électricité (cogénération)	Économique	Emplacements des bioraffineries, capacité, choix de produit,	Non	Finlande
Biagini et al. [38]	hydrogène	Économique	paramètres de fonctionnement, efficacité des processus, besoins énergétiques	Non	Toscane, Italie
Parker et al. [39]	biocarburants (éthanol, diésel)	Économique	Emplacement des bioraffineries, technologies, capacité	Non	Ouest de l'Amérique
Wang and al. [42]	F-t produit (diésel, gazoline)	Économique (NPV) Environnemental (GWP)	technologies, les conditions opératoires, le flux de chaque système, la consommation d'énergie de chaque unité, consumation d'électricité et de vapeur, tailles des équipements	Non	Pas d'étude de vue vu les variables de décision
You and al. [40]	Éthanol (simulation sur Aspen plus des procédés biochimiques et thermochimiques)	Économique (coût annualisé) Environnemental (CO_2eq/an) social (emplois	emplacement des bioraffineries, sélection de la technologie, investissement, planification de la production, contrôle des stocks, logistique	Multipériode (saisonnalité, dégradation, densité, etc.)	État de l'Illinois

		crées /an)			
Gebreslassie et al. [41]	FT Hydrocarbures (diésel, gazoline, carburéacteur)	Économique (coût annuel) Risque financier	sélection de la technologie, investissement, planification, logistique	Incertitude (coût de la MP, demande en carburants), Multipériode (saisonnalité, dégradation, densité, etc.)	État de l'Illinois
Wetterlund et al. [2]	DME, cogénération	Économique, énergétique, environnementale	Pas de modèle d'optimisation, évaluer les options selon des scénarios (prix du carburant, incitation politique, CO_2)	-	Suède
Jonsson et al, [43]	Extraction de la lignine, gazéification de la liqueur noire (électricité, DME), remplacement de la chaudière	Économique, environnemental	Comparer les alternatives selon le coût total annuel et les émissions de CO_2	-	Suède

ANNEXE B - DONNÉES À COLLECTER

Données techniques	Données économiques	Données spatiales
• Propriétés (densité, pouvoir calorifique, humidité) des types de biomasse retenus • Conditions opératoires des procédés de conversion • Productivité et consommation en ressources fossiles (RF) des méthodes de récolte de bois • Productivité et consommation en RF des méthodes de traitement des déchets de bois • Quantités de déchets de bois disponibles dans les sites potentiels d'approvisionnement • Quantités de déchets disponibles dans les scieries potentielles • Demande en produits chimiques et biocarburants retenus (varie selon les villes) • Capacité de chargement /consommation en RF des moyens de transport • Demande en syngaz pour remplacer la chaudière dans chaque usine de pâtes	• Investissements et coûts opératoires des technologies de conversion de la biomasse • Coûts d'approvisionnement en bois morts (varie selon la méthode de récolte du bois mort) • Coûts d'approvisionnement en déchets de bois (varie selon la méthode de récolte de bois et de récupération des déchets) • Prix d'achats des déchets de scieries • Coût de transport (varie selon la matière première ou le produit final) • Prix de vente des produits chimiques et des carburants retenus	Emplacements potentiels: • Sites d'approvisionnement en déchets de biomasse • Usines de pâtes (future BRFIV) • Scieries • Industries pétrochimiques